THE COST OF HEATING BUILDINGS FROM A CENTRAL HEATING STATION BY DIRECT LOW-PRESSURE STEAM

BY

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

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THE COST OF HEATING BUILDINGS

from

A CENTRAL HEATING STATION

by

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PRELIMINARY STATEMENT

Object of Work:- The object of this work was to determine experimentally the cost of supplying heat to buildings by direct low pressure steam from a central heating station. This cost is rated per sq. ft. of heating surface and per 1000 cu. ft. of contents heated per annum. Because the cost of operation, cost of installation, interest charges etc. are so different in different cases it was decided to determine the fuel cost alone. The total cost per sq. ft. of heating surface per annum or per 1000 cu. ft. of contents heated per annum may be found in any case from the fuel cost when the ratio of the cost of operation etc. per annum to the fuel cost per annum is known.

Necessary Determinations:- In order to determine the cost of coal for supplying steam to one sq. ft. of heating surface, or for heating 1000 cu. ft. of contents for any period of time, it is necessary to know:-

The heat emitted by direct radiator surface per sq. ft. during the period.

Ratio of cubic contents heated to sq. ft. of heating surface installed.

Percentage of the heat of the steam lost in the steam and return mains.

Efficiency of boiler and grate.

Cost of coal with reference to heating value.

Toward these determinations the following tests were made:-

Tests of direct low-pressure steam radiators.

Tests of the entire heating systems of several buildings.

Tests of the loss in low-pressure steam mains.

Boiler efficiency tests.

These tests are reported in Chapters I and II. In Chapter III is determined the cost of heating.

CHAPTER I.

HEAT GIVEN OFF BY DIRECT STEAM HEATING SURFACE

Considerations Leading to Tests:- The heat emitted by a direct steam radiator depends upon the temperature of the steam inside, the temperature of the air in the room, the construction of the radiator and the circulation of the air over its exterior surface. Radiation proper is considerably affected by the shape, size and spacing of the sections of a radiator, but since the radiant heat is but a small percentage of the total heat emitted, if we consider the steam and room temperatures as constant, the principal determining factor in the amount of heat given off by direct heating surface is the circulation of air over the surface. With ordinary direct steam radiators the circulation of the air over the surface depends upon the shape, the spacing and the height of the sections, the number of sections in one radiator and the location of the radiator in the room. Thus, a radiator of wide sections composed of three or four columns is less efficient than the ordinary two column radiator. The greater the space for air circulation between columns of the same section and between the different sections the more heat will the radiator give off. A high radiator is less efficient than a low one because the air is in contact with the surface longer and consequently the temperature difference between the steam and the air immediately surrounding the radiator is less. In all cases the radiator is surrounded by air which is considerably warmer than the air in other portions of the room. This variation increases with the size of the radiator and makes a large radiator less efficient than a small one. A radiator placed before an open window, or in any other place where there is naturally a current of air passing, will give off more heat than if placed near a solid wall. A radiator which rests six or eight inches from the floor and a considerable distance from the wall is more efficient than if placed very near the floor and wall. Radiators are usually tested by bringing each radiator to be tested into a room, which is fitted with the necessary apparatus, where each one is tested under the same and constant conditions. This gives correct results and is all that can be desired for the comparison of different types of radiators or for the determination of the performance of any particular type; but, from the above considerations, in order to determine the average performance of direct radiators it is desirable to test a large number of radiators of different heights, sizes etc. just as they are located in practice i.e. placed about four to six inches from the wall sometimes under a window, sometimes between two windows, etc., the steam temperature varying as it usually does. In consideration of these facts the tests of radiators and entire heating systems reported below were made.

An attempt was made at the same time to determine the average amount of heat required to maintain ordinary room temperatures in rooms of different sizes and with walls of different character and thickness. This, however, presented many difficulties some of which are:-

Difficulty of securing suitable rooms at a time suitable for testing.

Inadequate apparatus for testing several radiators at the same time.

Difficulty in securing near enough constant conditions for reliable determinations.

RADIATOR TESTS

METHOD OF PROCEDURE

Radiators Chosen:- For determining the average performance of direct steam radiators, good representative radiators varying in height and size and variously located were chosen and tested as nearly in place as possible. The system in which the radiators were installed was the overhead one pipe system at the University of Illinois.

Apparatus Used:- In the arrangement of the apparatus for these tests the object was to get the necessary apparatus connected to the radiator without moving it enough to effect the circulation of the air around it. This was done by combining in one piece as nearly as possible all the apparatus necessary for the test.

Description of Apparatus:- The apparatus used in these tests is shown in Fig. 1. It consists of a small cast iron box, A, 5" by 7" and 2 1/4" high, on the top of which is an extension which is threaded to fit the recess in an ordinary globe valve, B, from which the valve stem has been removed. The globe valve is fitted by means of the unions, C and D, to the radiator valve and radiator respectively, and serves as a trap for removing the water of condensation from the steam line. In one side of the

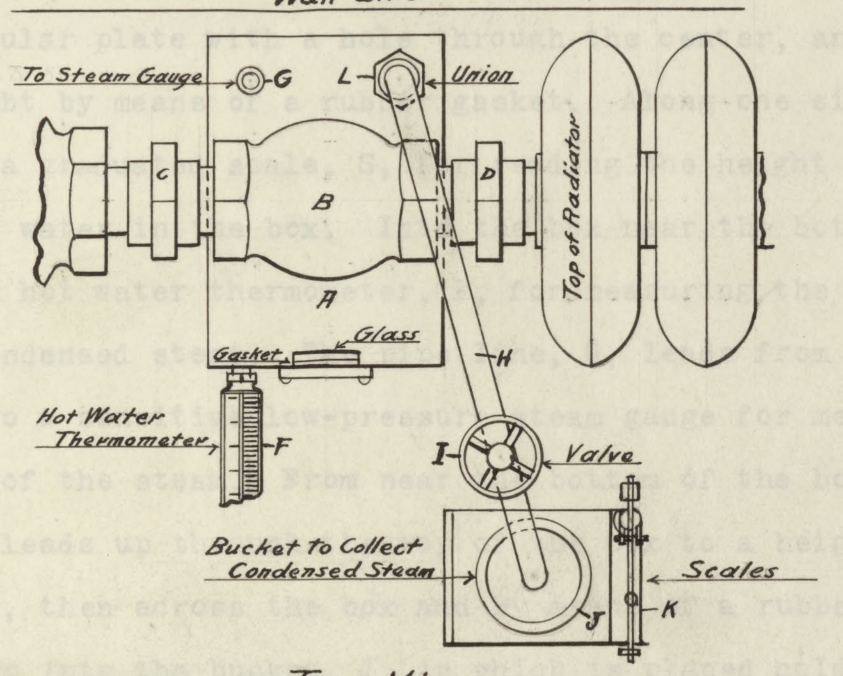


FIGURE I
APPARATUS CONNECTED TO RADIATOR
Scale: 3" = 1 Ft.
For Scales & Bucket, Scale: 1" = 1 Ft.

box, A, is fitted a glass E, which is kept in place by means of a rectangular plate with a hole through the center, and made steam tight by means of a rubber gasket. Along one side of the glass is a graduated scale, S, for reading the height of the collected water in the box. Into the box near the bottom is screwed a hot water thermometer, F, for measuring the temperature of the condensed steam. The pipe line, G, leads from the top of the box to a sensitive low-pressure steam gauge for measuring the pressure of the steam. From near the bottom of the box the pipe line, H, leads up through the top of the box to a height of about 15 inches, then across the box and by means of a rubber tube leads down into the bucket, J, in which is placed cold water to condense any steam which might be evaporated on account of the reduction of pressure on leaving the box. The bucket, J, rests on the scales, K, on which the condensed steam is weighed. In the pipe line, H. there is a union, L, which allows the line to be turned in any direction, and a valve, I, by means of which the condensed steam may be allowed to flow into the bucket, J, or be cut off. When the radiator valve is on the other side of the radiator the globe valve, B, must be turned one half turn on the box, A, so that the water will not back up in the radiator. This apparatus does not provide means of determining the amount of moisture in the steam. This had to be separately determined.

Distance Radiator is Moved and Consequent Effect on Results:- The total lenght of this apparatus with unions attached is about nine inches and ordinarily the radiator has to be moved this distance along the wall. Sometimes the distance moved is less, depending on the previous connections to the radiator. If this moving of the radiator brings more or less of it before a window (and especially if the window fits loosely and is on the exposed side of the building) the performance of the radiator will be affected slightly. Otherwise the performance will not be materially affected since the distance from the wall is not changed.

Two Pipe System:- The foregoing describes the application of the apparatus to the one-pipe system, all of the tests having been made upon radiators of this system. To use it with the two pipe system a greater change would have to be made in the connections or the radiator would have to be moved farther out of place.

Mehtod of Making a Test:- Connect the apparatus as shown in Fig. 1, and let the radiator work until average conditions are obtained.

Open the valve I and bring the water in the box down to the height desired at starting (Not too low).

Place a bucket containing a weighed amount of cold water on the scale and drop the rubber tube in it.

Observe the time, temperature of condensed steam, steam pressure, height of water in the box, weight on scales and temperature of surrounding atmosphere.

By means of the valve I, keep the water of condensation running into the bucket at as nearly a uniform rate as possible.

Make the above mentioned observations at regular intervals and as often as convenient, noting carefully any irregularities.

To stop the test, bring the water in the box to the same level as at starting, close the valve I, make the usual observations, and weigh the water in the bucket.

Observations for Tests on Radiator Alone:- In the tests made upon radiators alone the following observations were made:-

Radiator.

Type . . . .

Number of Sections . . . .

Number of Columns. . . . .

Height, inches . . . .

Rated Surface, Sq. ft. . . . .

Measured Surface, sq. ft.. . . . .

Weight per section including one nipple. . . . . . .

Time.

Steam pressure, at 10 minute intervals . . . .

Scale reading at 10 minute intervals . . . .

Temperature of condensed steam at
10 minute intervals . . . .

Temperature ofRoom at 10 minute intervals . . . . .

Temperature of Outside air at 30 minute intervals. .

Water in collecting devices at beginning and end . .

Additional Observation for Tests on Room:- For tests on the room as well as the radiator, to these observations were added:-

Room.

Number . . . .

Building . . . .

Floor . . . .

Location on floor . . . .

Used for . . . .

Walls.

Height . . . .

Area . . . .

Material . . . .

Thickness . . . .

How exposed. . . . .

Glass area . . . .

Door area. . . . .

Ceiling.

Material . . . .

Area . . . .

How exposed. . . . .

Floor

Material . . . .

Area . . . .

How exposed. . . . .

Kind of ventilation.

Actual Heating Surface:- In measuring the actual heating surface of radiators the following method was used:-

For that portion of the column which is regular in shape the average perimeter was found by fitting strips of paper around it in several places. This average perimeter multiplied by the length gives the area of the part with regular outlines. For that part of the surface which is irregular thin paper was fitted over it and the area of the paper was measured with a planimeter.

Steam Pressure:- The steam pressure was measured by means of a carefully calibrated, sensitive, low-pressure steam gauge.

Temperature of Room:- For measuring the temperature of the atmosphere surrounding the radiator the thermometers were placed so as to get the average temperature of the room. This is the temperature used in calculating the heat given off per hour, per square foot, per degree difference temperature rather than that immediately surrounding the radiator.

RESULTS

Table 1 gives the results of these tests. With the exception of tests 3, 4, 5 and 21, these tests may be regarded as giving average results. Tests 3 and 4 were made with no air valve on the radiator, this being the condition under which the radiator had been working. The effect is evident and the results show that not more than one half of the radiator was working. Test No. 5 was made on the same radiator with an air valve on the section at which the steam entered. The results show that about two-thirds of the radiator was working. Test No. 10 has been disregarded because of an inaccuracy in measuring the condensed steam. Test 21 is regarded as inaccurate because the water had backed up somewhat in the radiator before the test was started.

The radiator performance is considerably higher in tests 1 and 2 than in the other tests and is believed to be higher than

TABLE 1 - RESULTS OF RADIATOR TESTS AND HEAT REQUIRED TO MAINTAIN LIVING TEMPERATURES IN ROOMS

Room	(1)	Location of Room	201 M.E. Lab.		202 M.E. Lab., 2nd Floor, South East Corner							109 Eng. Hall, 1st Floor			205 Eng. Hall, 2nd Floor, S.E. Cor.				Hall, 2nd Floor, Eng. Hall					312 Eng. Hall, 3rd Floor, W.			Eng. Hall 3rd Floor, N.W.	
	(2)	Glass Area Exposed, Sq. Ft.	66		283.3							99.6			236.3									107.4			105	
	(3)	Equivalent Glass Area of Walls, Ceiling & Floor Exposed	81.2		225.7							67.4			145									124.7			143.2	
	(4)	Total Equivalent Glass Area Exposed, Sq. Ft.	147.2		509							167			381.3									232.1			248.2	
	(5)	Cubic Contents, Cu. Ft.	7094		16795							6468			12796									5928			4226	
Radiator	(6)	Type	Amer. Rad. Co. "Ideal Steam"		American Radiator Company "Ideal Steam"							American Radiator Co. "Ideal Steam"			American Radiator Co. "Ideal Steam"				American Radiator Co. "Ideal Steam"					American Radiator Co. "Ideal Steam"			Amer. Rad. Co. "Ideal Steam"	
	(7)	Number of Columns	2		2							2			2				2					2			2	
	(8)	Number of Sections	23		19							20			16				23					12			16	
	(9)	Height, inches	41		41							32			32				45.5					37.75			32	
	(10)	Rated Surface, Sq. Ft.	92		76							66.67			53.33				115					48			53.33	
	(11)	Measured Surface, Sq. Ft.	87.9		72.65							67.11			53.72				114.54					45.95			53.72	
	(12)	Weight per Section including one Nipple, lbs.	25.25		25.25							23.25			23.25				34					25.25			23.25	
	(13)	How Painted	Bright Aluminum		Bright Aluminum							Brown			Bright Aluminum				Rusted Brown					Bright Aluminum			Bright Aluminum	
Results	(14)	Test Number	1	2	3	4	5	6	7	8	9	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
	(15)	Duration of Test, Hrs.	1	2	1	1	1	2	1	1	1	1	1	0.5	1	1	1	1	1	1	1	0.5	0.5	1	1	1	1	1
	(16)	Mean Steam Pressure, Gauge	13.6	12.1	6.2	8.9	6.6	9.35	4.4	8.45	4.85	5.9	6.7	6.5	4.4	7.7	7.8	7.0	6.4	7.0	7.8	6.5	7.1	6.1	7.5	5.9	7.1	6.8
	(17)	Mean Temperature of Entering Steam, °F.	247	244	230.2	236.8	231.3	237.9	225.5	235.8	226.7	229.5	231.5	231	225.5	234	234	232.3	230.8	232.3	234.2	231	232.5	230	233.5	229.5	232.5	231.8
	(18)	Mean Temperature of Room, °F.	70	70	72	67	68.5	71	75.5	72	73	65.5	69	70	70	67	67	68.5	76.5	73.3	74.2	75.5	75.5	72	79	81	73	73.5
	(19)	Temperature Difference Steam & Room, °F.	177	174	158.2	169.8	162.8	166.9	150	163.8	153.7	164	162.5	161	155.5	167	167	163.8	154.3	159	160	155.5	157	158	154.5	148.5	159.5	158.3
	(20)	Mean Temperature of Outside Air, °F.	25.5	25.5	34	33	34	44	46	41	43	41	44	40	37.5	40	43	43.5	40	46.5	50.5	61	61	51	51.5	53	37	39
	(21)	Temperature Difference Room & Outside Air, °F.	44.5	44.5	38	34	34.5	27	29.5	31	30	24.5	25	30	32.5	27	24	25	36.5	26.8	23.7	14.5	14.5	21	27.5	28	36	34.5
	(22)	Mean Temperature of Condensed Steam, °F.	238	234.5	216	226	219	225	213	224	214.5	223	224	224	216	223	223	220.5	223.5	225	226.5	225	226	221.5	226	223	224.5	224
	(23)	Weight of Steam Condensed, lbs.	31.75	59.75	8.75	11.13	14.5	42.75	17.88	22.25	19.5	18.25	19.13	9.13	14.63	14.88	15.13	15.13	25.13	28.13	29.56	18.38	14.13	12.38	11.56	11.19	14.38	14.44
	(24)	Pounds of Steam Condensed per Hour per Sq. Ft.	.361	.340	.120	.153	.200	.294	.246	.306	.268	.270	.285	.270	.272	.277	.282	.282	.219	.246	.258	.321	.247	.269	.252	.244	.268	.269
	(25)	Heat Absorbed per Pound of Steam, B.t.u.	903.1	905.5	914.5	907	912	903.6	911.4	903.9	910.3	940.8	940.5	940.4	946.6	942.3	942.4	944.8	940.8	939.8	938.9	939.4	938.8	942.5	939.1	940.9	940.3	940.6
	(26)	Total Heat Given off from Radiator per Hour, B.t.u.	28673	27052	8002	10090	13224	19315	16291	20112	17751	17170	17992	17172	13849	14021	14259	14287	23642	26437	27754	34532	26530	11668	10856	10529	13522	13582
	(27)	Same per Degree Diff. Temp. of Steam & Room	162	155.5	50.6	59.4	81.2	115.7	108.6	122.8	115.5	104.7	110.7	106.7	89.1	84	85.4	87.2	153.2	166.3	173.5	222.1	169.0	73.9	70.3	70.9	84.8	85.8
	(28)	Same per Sq. Ft. of Actual Heating Surface	1.84	1.77	.70	.82	1.12	1.59	1.49	1.69	1.59	1.56	1.65	1.59	1.66	1.56	1.59	1.62	1.34	1.45	1.51	1.94	1.48	1.61	1.53	1.54	1.58	1.60
	(29)	Total Heat per Hr. from Pipes in Room at 1.6 B.t.u./Sq.Ft.	3717	3654		8966	8596	8813	7920	8650	8116	1968	1950	1932			8233	8075							3198	3074		0
	(30)	Heat from Radiators + Heat from Pipes	32390	30706		19056	21820	28128	24211	28762	25867	19138	19942	19104			22492	22362							14054	13603		13582
	(31)	Same − Heat Absorbed in Raising Temp. of Room	32390	30881		19446	21820	27414	22992	29120	25319	18522	19726	19104			22532	22108							13787	13283		13453
	(32)	Same per Cu. Ft. Contents per Degree Diff. Room & Outside	.1026	.0978		.0341	.0377	.0604	.0464	.0559	.0503	.1169	.1220	.0985			.0734	.0691							.0846	.0800		.0923
	(33)	Heat Required for One Change of Air per Hour, B.t.u.	5856	5856		10554	10709	8257	8992	9492	9162	2918	2950	3546			5626	5848							2937	2985		2660
	(34)	Heat Transmitted through Walls = (31) − (33)				8912	11112	19157	14000	19628	16157						16906	16260							10850	10298		10793
	(35)	Same per Sq. Ft. Equivalent Glass Area				17.5	21.8	37.6	27.5	38.6	31.7						44.3	42.6							46.8	44.4		43.5
	(36)	Same per Degree Diff. Temp. of Room & Outside Air				.52	.63	1.39	.93	1.24	1.06						1.85	1.71							1.70	1.58		1.26
	(37)	Changes of Air per Hr. Assuming Coefficient for Glass = 1.00	4.41	4.15		.20	.40	1.66	.89	1.41	1.10	4.95	5.27	3.97			2.38	2.15							2.17	2.18		3.22

is ordinarily obtained in practice because of exceptionally good circulation of the air around this radiator.

Results in Brief:- With the exceptions noted above the average results of these tests are given in brief according to the height of the radiator in table 2 below:-

TABLE 2.

AVERAGE B. t. u. TRANSMITTED PER HR. PER SQ. FT. OF RADIATOR SURFACE PER PEGREE DIFFERENCE BETWEEN TEMPERATURE OF STEAM AND ROOM FOR RADIATORS OF DIFFERENT HEIGHT.

Height of Radiator, inches	Test Number	Av. B.t.u. Transmitted per Hr. per sq. ft. Radiator Surface per Degree Difference between Temperature of Steam and Room.
32	11,12,13,14,15,16,17,26 and 27	1.60
38	23, 24, 25	1.56
41	1, 2, 6, 7, 8 and 9	1.66
41	6, 7, 8 and 9	1.59
45	18, 19, 20 and 22	1.45
32, 38, 41, 45	All the above tests	1.58

This table gives an average value for the radiation factor and shows how it is affected by variation in the height of the radiators. Since the radiator in tests 1 and 2 was working under exceptionally good conditions, the second value for the 41 inch radiators is to be chosen for comparison according to height. It will be noticed that even this smaller value is greater than the factor for 38 inch radiators. This is due to the fact that both have the same pattern except that the 41 inch radiator has longer legs allowing better circulation of the air around it. The conditions under which the 45 inch radiator worked were hardly as good as the average, but the low factor of radiation is due mostly to its height. Too much emphasis should not be placed on this comparison according to height, however, for the object of the tests was to obtain average results for these most commonly used heights and, consequently, more attention has been paid to obtaining average conditions for the set of tests as a whole than to similar conditions for radiators of different heights.

Average of Results:- These results indicate that the average of the factor of radiation should be about 1.6 B.t.u. per hour per sq. ft. heating surface per degree difference between the temperatures of steam and room. This value is somewhat lower than is usually assumed, but, although the tests were of comparatively short duration, the readings were frequent and care was exercised in taking them correctly and it is believed that the results are reasonably correct.

HEAT REQUIRED TO MAINTAIN LIVING TEMPERATURES

Effect of Pipes:- In calculating the heat required to maintain living temperatures in the rooms, the heating effect of any steam pipes in the room must be taken account of. The radiation factor for these pipes was assumed to be 1.6 B.t.u. per sq. ft. per hr. per degree difference temperature of steam and room. This is rather low for pipe radiation in some cases, but as these pipes are usually placed where the circulation of the air is not very good, and as they extend the full height of the room, it is believed that this value is not far from the average.

Change of Room Temperature:- Again, if the temperature of the air in the room changes while the test is being made, the heat required to change the temperature by this amount must be accounted for in order to determine the heat per unit cubic content necessary to maintain constant temperature, as well as to determine the heat carried away through the walls.

Heat Transmitted through Walls per sq. ft. Equivalent Glass Area:- Besides the heat absorbed in changing the temperature of the room there must be deducted from the total heat furnished to the room the heat required to warm the air admitted during the test. The cold air admitted ranges from about one change of air per hour for rooms of ordinary construction with all doors and windows closed to several changes per hour for well ventilated rooms, the number of changes depending on the cubic contents allowed per occupant. In these tests it was assumed that the air changed once per hour in calculating the heat transmitted through the walls. In finding the equivalent glass area of the walls, the relative transmitting power of different materials was taken from Mr. Alfred R. Wolf's translation of "The Investigations of the German Government". Many of the radiator tests are not suitable for this investigation. The following are the exclusions with reasons for same:-

Test number 3, another radiator working in the same room.

Tests 4 and 5, the amount of heat given off in comparison to size of room too small to be considered accurate.

Tests 14 and 15, another radiator working in same room.

Tests 18, 19, 20, 22, the room was a large corridor in which other radiators were at work, and of which the cubic content is indeterminant.

Tests 23 and 26, the effect of another radiator was realized in each.

Results in Brief:- The average of these results is given in brief in Table 3.

TABLE 3.

HEAT TRANSMITTED BY WALLS AND HEAT REQUIRED TO MAINTAIN LIVING TEMPERATURES.

Test Number	Average B.t.u. per cu.ft. contents per Degree Diff. Temp. of Room and Outside Air per Hr. Required to Maintain Constant Temperature	Average B.t.u. Transmitted by Walls per sq. ft. Equivalent Glass Area per Degree Difference Temperature of Room and Outside Air per Hour.
1,2,6,7,8,9,11, 13,16,17,24,25 and 27	.0822	
6,7,8,9,16,17,24, 25 and 27	.0680	1.41

The value 1.41 in the last column was calculated by assuming one change of air per hour. Table 1, line 37, gives the changes of air per hour when this coefficient for glass area is assumed to be 1.00.

TESTS OF ENTIRE HEATING SYSTEMS OF BUILDINGS

Object of Tests:- The object of these tests was to determine the amount of heat given off per unit surface per unit time per degree difference between the temperatures of steam and surrounding air throughout the entire heating system of a building. This includes all the heating surface in the building.

Systems Tested:- The heating systems chosen for these tests were those of the Engineering Building, The Physics Building, The Auditorium and The Woman's Building at the University of Illinois. These were chosen more for the reason that the water of condensation could be disposed of at these buildings than for any other reason. As the buildings are somewhat different in character and are used quite differently, they represent fairly well the conditions met with in public and semi-public buildings.

Buildings Tested:- The Engineering Hall is a large brick building composed of a sub-basement (extending under only a part of the building and used for lighting and heating alone), a basement, three stories and attic. The basement is entirely above grade level and the walls are faced with stone up to the window sills of the first floor above the basement. The building comprises lecture rooms, drafting rooms, laboratories and offices.

The one pipe overhead feed system of direct steam heating is used. Steam is furnished from a central heating station 200 ft. from the building.

The Physics Building is a large, fire proof, brick building just completed. It consists of a basement which is beneath grade level, four stories and attic. It comprises lecture rooms, laboratories, offices and, separated from the main building by an open court, a machine shop in one end of which is located the tempering and fan rooms. The building is heated principally by direct cast iron heating surface. The two main lecture rooms are heated by the indirect fan system and the air for ventilation is tempered by indirect coils. All of the indirect coils are fitted with thermostatically controlled diaphram valves and hand valves. All of the radiators are fitted with thermostatic valves giving a uniform regulation of temperature throughout the entire building. The steam is admitted at about 3 lbs. pressure, gauge, and a vacuum of about 6 ins. is kept in the return line by a pump located in the basement. Steam is furnished from the central heating station about 200 ft. away.

The Auditorium is a brick building composed of a basement, partly beneath grade level, one large audience room of about 2,200 seating capacity and consisting of a parquet and one balcony, and a lobby of two stories with passage ways leading to the different entrances. It also has an attic about 8 ft. high over the entire building except the skylight in the center which is about 12 ft. in diameter. The building is heated by direct heating surface entirely. Most of the radiators are placed in the lobby and passages, but some few are placed in the main room on each floor. There are also a few small coils around the skylight. The steam is supplied from the central heating station at a distance of 2135 ft.

The Woman's Building is another brick structure which comprises offices, laboratories, reception rooms, a gymnasium and bath and dressing rooms. It has a basement partly beneath grade level and only partially heated. Part of the building is three stories above the basement and a part is only two stories in which part on the second floor is the gymnasium. Most of the heating surface is direct surface distributed throughout the building. There is a coil of about 650 sq. ft. indirect surface in the basement and another of about 250 sq. ft. higher up in the building. The steam is supplied from a central heating station at a distance of 1880 ft.

METHOD OF CONDUCTING TESTS

All of these tests were conducted in the same manner. The method in brief consisted in determining the amount and condition of the live steam entering the building, the condition of the condensed steam leaving the building, the temperature of the building and the sq. ft. of radiating surface installed. From these determinations was found the heat emitted per sq. ft. of heating surface per hr. per degree difference between temperature of steam and room.

Amount of Steam Condensed:- To determine the amount of steam condensed, except in the Physics Building, the connections between the traps in the returns and return mains were closed and pipe lines were run from the traps into tanks placed upon scales for weighing the water. In these tanks, which were used in duplicate in each case, the condensed steam was collected under cold water to prevent reevaporation. After being weighed the water was emptied into the sewer. The only change made in the case of the Physics Building was that the pipe lines were run from the pump instead of from the traps, there being no traps in the return line at this point. The only difficulty met with in this method of procedure was that some of the traps and the pump in the Physics Building required constant and careful attention to prevent some steam from blowing through with the water.

Temperature and Pressure of Entering Steam:- The pressure of the entering steam was determined by a sensitive low pressure gauge placed on the steam main "after" the regulating valve. The temperature was taken from the steam tables.

Moisture in Steam:- The moisture in the steam was determined by a separating calorimeter placed on the main just "after" the regulating valve.

Temperature of Return Water:- The temperature of the return water of condensation was measured by thermometers placed in wells which were inserted in the water lines just above the weighing tanks.

Temperature of Building:- The mean temperature of the building was found by placing thermometers throughout the building in such places as to get the best average temperature.

Frequency of Readings:- The temperature of the water of condensation was read once for each tank full while the trap was discharging into the tank. The time between these readings ranged between five and twenty minutes, depending upon the rate of condensation. The pressure of the steam was read at the same time as the temperature of the condensed steam. Temperatures of the building and outside air were read at half hour intervals.

RESULTS

Table four gives the results of these tests on four buildings under service conditions. In the Engineering Hall, the Auditorium and the Woman's Building the heating surface given includes all of the exposed pipes in the building, and in the case of the Woman's Building it includes the direct equivalent of the small amount of indirect surface. The heating surface of the Physics building includes the actual surface of the tempering and reheating coils and 2615 sq. ft. were added for the heating surface equivalent of the pipes. This pipe surface equivalent was determined by a test of the condensation from the pipes plus 114 sq. ft. of cast iron surface. From the amount of heat lost in this way the heating surface equivalent of the pipes was determined by allowing 1.6 B.t.u. as the heat emitted per sq. ft. per Hr. per degree difference between the temperatures of steam and room. This test is included in table 5. During the test

TABLE 4 - RESULTS OF TESTS OF ENTIRE HEATING SYSTEMS OF BUILDINGS

	Building Tested	Engineering Hall			Physics Building	Auditorium		Woman's Building
(1)	Date of Test	2/10/09	1/19/10	2/12/10	1/18/10	2/12/09	2/13/09	3/4/09
(2)	Duration of Test, Hours	8	8	7	7	10	5	10
(3)	Mean Steam Pressure, Gauge	7.65	7.3	7.8	3.0	5.0	4.8	5.1
(4)	Mean Temp. of Entering Steam °F	233.8	233	234.2	221.5	227.1	226.6	227.4
(5)	" " of Building, °F	70	73.2	71	70.2	68	62.5	70
(6)	Temperature Difference of Steam and Room, °F	163.8	159.8	163.2	151.3	159.1	164.1	157.4
(7)	Mean Temp. of Outside Air, °F	21.5	42.3	22.8	35	43	36.5	37.5
(8)	Temperature Difference of Room and Outside Air, °F	48.5	30.9	48.2	35.2	25	26.0	32.5
(9)	Mean Temp. of Condensed Steam, °F	212	216	217	202.5	210	207	212.5
(10)	Moisture in the Steam, Percent	1.6	1.0	0	0	10.8	12.7	10.0
(11)	Total Weight of Condensed Steam, lbs.	28457	27665	25830	12146	10689	5751	11555
(12)	Same per Hour, lbs.	3557.1	3458.1	3690	1735.1	1068.9	1150.2	1155.5
(13)	Total Heat in 1 lb. of Moist Steam, B.t.u.	1138.1	1143.5	1153.3	1149.5	1048.1	1029.7	1055.9
(14)	" " " 1 lb of Condensed Steam, B.t.u.	180.9	185.0	186.0	171.2	178.9	175.8	181.4
(15)	Heat Lost by each Pound of Steam, B.t.u.	957.2	958.5	967.3	978.3	869.2	853.9	874.5
(16)	Factor of Condensation = (15) ÷ 965.7	.9912	.9925	1.0017	1.013	.9001	.8842	.9056
(17)	Equiv. Cond'n per Hr. at & to 212°F = (12) × (16)	3525.6	3432.2	3696.3	1757.7	962.1	1017.	1046.4
(18)	Horse Power Consumed = (17) ÷ 34.5	102.2	99.48	107.14	50.95	27.9	29.5	30.33
(19)	Total Heat Radiated per Hr., B.t.u. = (12) × (15)	3404680	3314618	3569340	1697450	929090	982155	1010485
(20)	Total Sq. Ft. of Heating Surface. incl'g Exposed Pipe	11000	11000	11000	14620	4820	4820	5735
(21)	Steam Condensed per Sq. Ft. of Heating Sur. per Hr., lbs	.323	.314	.335	.119	.222	.239	.202
(22)	B.t.u. Emitted per Sq. Ft. Heat. Sur. per Hr. per Deg. Diff Temp.	1.89	1.89	1.99	.77	1.21	1.24	1.12
(23)	Total Cubic Contents, Cu. Ft.	778110	778110	778110	849550			349735
(24)	Exposed Area including Glass, Sq. Ft.	38710	38710	38710	39982			27231
(25)	Glass Area Exposed, Sq. Ft.	10676	10676	10676	9387			3220
(26)	Total Equivalent Glass Area Exposed, Sq. Ft.	14990	14990	14990	15690			8040
(27)	B.t.u. per 1000 Cu. Ft. Content per Deg. Diff. Temp. Rm. & Outside	90.2	137.9	95.2	56.8			89.0
(28)	Changes of Air per Hr. Assuming Coeff'nt for Glass = 1.00	3.88	6.51	4.17	2.11			3.41

of the Physics Building the steam was left on the tempering coils all the time and the fan was run about two hours in the forenoon to heat the lecture rooms. The direct radiators, the tempering coils, and the amount of air passing through the reheating coils were all thermostatically controlled so that this test represents actual heating conditions in the Physics Building. The last two items of table 4 give the values of the B.t.u. per 1000 cubic feet contents heated per degree difference between the temperatures of the building and outside air, and the changes of air per hour. In calculating the changes of air per hour the coefficient for equivalent exposed glass area was assumed to be 1.00 B.t.u. per square foot per hour per degree difference between the temperatures of the building and the outside air. The values of these items for the Auditorium were not calculated because the the cubic contents and equivalent exposed glass area were not determined.

The fact that the performance of the radiators in the Engineering Hall is much higher than of those in the Auditorium and Woman's Building may be accounted for in the following ways. The heating surface in the Engineering Hall is composed mostly of small and well distributed radiators, large radiators being placed only in the halls. All of the cast iron radiators are of the two column type. Including the exposed pipe surface, there is 3820 sq. ft. of wrought iron heating surface in the building. The wrought iron radiators consist of four rows of one inch pipe connected at top and bottom with cast iron headers. They are only two ft. high and have large spaces for air circulation. These radiators are placed in recesses left in the walls under the windows, with the front entirely open to the room and only a very thin wall between them and the outside air. While this position may somewhat decrease the draft of cold air from the room, it is probable that the thin wall on the outside is the cause of an increase in the performance of the radiators. The steam being dryer here than at the other buildings, there would probably be better circulation of the steam. On the other hand the radiators in the Auditorium and Woman's Building are practically all cast iron of the three column type. The radiators in the Auditorium being placed in the lobby, the air assumes a higher temperature there than the average for the building causing a smaller difference of temperature between steam and room. All of these conditions tend to make the heating surface in the Engineering Hall appear more efficient than that in the Auditorium and Woman's Building. Since the heating surface in the Physics building is automatically shut off as the temperature rises it is not surprising that the performance is much lower than for the other buildings.

Table 5 gives the results of comparative tests on the Engineering Hall and the Physics building. The system in the Engineering Hall is fitted with hand valves while that in the Physics Building is thermostatically controlled throughout. In the Physics building the air required for ventilation is arranged

TABLE 5 – RESULTS OF COMPARATIVE TESTS ON TOTAL HEATING SYSTEMS OF BUILDINGS

	Building Tested	Physics Building	Engineering Hall	Physics Building	Engineering Hall	Physics Building	Physics Building	Pipes in Physics Bldg.
(1)	Date of Test	1/18/1910	1/19/1910		2/12/1910		2/18/1910	2/18/1910
(2)	Duration of Test, Hours	7	8	coils shut off	7		7	coils on 2
(3)	Mean Steam Pressure, Gauge	3.0	7.3	3.0	7.8	3.0	3.0	3.0
(4)	Mean Temp. of Entering Steam, °F	221.5	233	221.5	234.2	221.5	221.5	221.5
(5)	" " " Building, °F	70.2	73.2	71.5	71	70.4	71.6	65
(6)	Temperature Difference of Steam and Room °F	151.3	159.8	150.0	163.2	151.1	149.9	156.5
(7)	Mean Temp. of Outside Air, °F.	35	42.3		22.8		17.0	10
(8)	Temperature Difference of Room and Outside Air, °F.	35.2	30.9	29.2	48.2	47.6	54.6	55
(9)	Mean Temp. of Condensed Steam, °F	202.5	216	200.7	217	192.8	199.3	175
(10)	Moisture in the Steam, Percent.	0	1.0	1.5	0	1.0	0	0
(11)	Total Weight of Condensed Steam, lbs.	12146	27665	8660	25830	12151	26489	1360
(12)	Same per Hour, lbs.	1735.1	3458.1	1082.5	3690	1735.9	3784.1	680
(13)	Total Heat in 1 lb. of Moist Steam, B.t.u.	1149.5	1143.5	1135.1	1153.3	1139.9	1149.5	1149.5
(14)	" " " 1 lb. of Condensed Steam, B.t.u.	171.2	185.0	169.4	186.0	161.5	168.0	144.5
(15)	Heat Lost by each Pound of Steam, B.t.u.	978.3	958.5	965.7	967.3	978.4	981.5	1005.0
(16)	Factor of Condensation = (15) ÷ 965.7	1.013	.9925	1.000	1.0017	1.013	1.016	1.041
(17)	Equiv. Cond'n per Hr. at & to 212°F = (12) × (16)	1757.7	3432.2	1082.5	3696.3	1758.5	3844.6	709.9
(18)	Horse Power Consumed = (17) ÷ 34.5	50.95	99.48	31.38	107.14	50.97	111.44	20.52
(19)	Total Heat Radiated per Hr., B.t.u. = (12) × (15)	1697450	3314618	1045370	3569337	1698405	3714094	683400
(20)	Total Sq. Ft. of Heating Surface incl'd. Exposed Pipe	14620	11000	12265	11000	12265	14620	2729
(21)	Steam Condensed per Sq. Ft. of Heat. Sur. per Hr., lbs	.119	.314	.088	.335	.142	.259	Refer to,- P.17 Last ¶ P.19 Last ¶ P.20, Last ¶
(22)	B.t.u. Emitted per Sq. Ft. Heat. Sur. per Hr. per Deg. Diff. Temp.	.77	1.89	.57	1.99	.92	1.69	
(23)	Total Cubic Contents, Cu. Ft.	849550	778110	849550	778110	849550	849550	
(24)	Exposed Area including Glass, Sq. Ft	39982	38710	39982	38710	39982	39982	
(25)	Glass Area Exposed, Sq. Ft.	9387	10676	9387	10676	9387	9387	
(26)	Total Equivalent Glass Area Exposed, Sq. Ft.	15690	14990	15690	14990	15690	15690	
(27)	B.t.u. per 1000 cu. Ft. Contents per Deg. Diff. Temp Rm. & Outside	56.8	137.9	42.1	95.2	42.0	80.1	
(28)	Changes of Air per Hr. Assuming Coefficient for Glass = 1.00	2.11	6.51	1.31	4.17	1.29	3.39	

for by manipulation of the heating coils and fans and the direct surface heats the air to the desired temperature, while in the Engineering Hall the amount of heat given off is kept practically constant and the temperature is regulated by opening the windows and allowing the heated air to escape. The object of these tests was to determine the saving effected by the thermostatic control in the Physics Building. The test dated January 18, 1910 is given in table 4 and has already been considered. During the comparative tests dated January 19, 1910 and February 12, 1910 all of the tempering and reheating coils in the Physics building were shut off by the hand valves and the direct surface alone was tested. The test of the Physics building dated February 18, 1910 was made with the steam turned on in the tempering and reheating coils and the fans running the entire time, the object being to determine the relative steam consumption of this system with and without the indirect surface. The last test in the table, as before stated, was made to determine the loss of heat in the supply and return pipes inside the building. The heating surface given includes 114 sq. ft. of cast iron radiator surface.

The superior economy of the Physics Building system is at once evident. Items (21) and (22) are calculated for the heating surface given as explained above. The small values of these items during the first three tests of the Physics Building system indicate simply that the steam was automatically shut off from a part of the heating surface varying from about one half to almost two thirds of the system. These tests and a comparison of the two systems are given in detail by Mr. N. W. Overstreet of the University of Illinois in his thesis for B. S. degree in Architectural Engineering. It is, however, desirable to emphasize here the enormous saving of steam or fuel in mild weather, in addition to the satisfactory control of the temperature and ventilation, brought about by the automatic control of the heating system as shown by item (27) table 5.

Significance of Results:- The averages of the most important of the results given in table 4 are restated briefly in table 6. In these averages the results of each test are valued in proportion to the magnitude of the system tested. Where a value for the Physics Building is included it is taken as a mean of the values in the tests of January 18, 1910 and February 18, 1910 table 5, which should give about the correct average value for all winter weather.

TABLE 6-RESULTS IN BRIEF OF TESTS ON ENTIRE HEATING SYSTEMS OF BUILDINGS

Systems for which average is calculated.	Item	Value
Engineering Hall, Auditorium and Woman's Building	B.t.u. Emitted per hour per sq. ft. of heating surface per degree difference temperature of steam and room	1.55
Engineering Hall, Physics Building and Woman's Building	B.t.u. per 1000 cu. ft. of contents per degree difference temperature of room and outside air	86.3
Engineering Hall, Physics Building and Woman's Building.	Changes of Air per hour Assuming the coefficient for equivalent exposed glass area = 1.00	3.69
Engineering Hall, Physics Building and Woman's Building.	Cu. ft. of contents heated per sq. ft. of radiator surface installed	75.5

At first sight the value 1.55 for the B.t.u. emitted per sq. ft. of heating surface per hour per degree difference of temperatures of steam and room appears lower than is ordinarily used in calculating the heating surface required. This coefficient is usually taken as about 1.70 for the radiator surface alone. The two values are not far from equivalents, however, for if we assume that the exposed pipe surface is say 10 per cent of the radiator surface installed, the value in the table becomes $\frac{1.55}{.9} = 1.72$ for radiator surface alone.

The table further indicates that on an average such buildings require about 86.3 or say 85 B.t.u. per 1000 cu. ft. of contents per degree difference of room and outside temperatures, with about 3.7 changes of air per hour, to maintain living temperatures. For any other number of changes of air per hour the additional heat necessary to maintain living temperatures may be approximated thus:-

1 B.t.u. heats approximately 55 cu. ft. of air 1 degree F.

$\frac{1000}{55} =$ B.t.u. required to heat 1000 cu.ft. 1 degree F.

If d n = the number that the changes per hour differ from 3.7, then, B.t.u. per 1000 cu. ft. contents per degree difference temperature per hour $= 85 \pm d\ n \times \frac{1000}{55}$

CHAPTER II.

LOSSES IN A CENTRAL STATION STEAM HEATING SYSTEM

LOSS OF, OR DROP IN, PRESSURE IN MAINS

Object of Tests:- The object of these tests was to determine how rapidly the pressure in a low-pressure steam heating main drops with increasing distance from the heating station.

METHOD OF PROCEDURE

Placing Gauges:-In these tests gauges were placed along the mains at such points as it was desired to determine the pressure. Carefully calibrated low-pressure gauges were used, and they were placed in the bleeders from the mains to avoid shutting off the steam while putting them on. The centers of the gauges were elevated so that the accumulation of water in the bleeders would not affect the gauge reading.

Running Conditions:- During these tests the steam was left turned on at all of the buildings and the steam was supplied under working conditions, three different pressures being used.

Simultaneous Observations:- In order to take simultaneous readings of the gauges, most of them were read by a short "switch off" of the lights in the main tunnel. All of the gauges in this part of the tunnel were read immediately after the lights came on again and, consequently, the observations in no case could lack more than a few seconds of being simultaneous. Those gauges in the branch tunnels were read by watches which were previously set with that of the operator of the main tunnel light switch. As the pressure was comparatively steady, there could have been but slight error, if any, due to non-simultaneous observations.

Duration of Tests and Frequency of Observations:- Of the three tests made the first two were conducted for one hour each and the third for two hours. In all three tests the observations were taken at five minute intervals, thus giving thirteen observations each for the first two tests and twenty five for the third test.

RESULTS

In table 7 are given the results of these tests. Fig. 2 shows the lay out of the system, the location of the gauges, the average pressures observed and the approximate velocity of the steam at each of the gauges for two of the tests.

Accuracy of Results:- While the tests were short, the observations were frequent, and the results are believed to be reasonably accurate.

Steam Passing and Approximate Velocity:- In the tables the values in the columns marked "Steam passing per Hour" and "Approximate Velocity of Steam" are approximate being calculated as follows:-

Let R = Total radiating surface beyond the point in question, including the equivalent heating surface of the mains, in sq. ft.

TABLE 7—VARIATION OF PRESSURE WITH VARIATION IN DISTANCE AND VELOCITY

Test Number				1		2		3	
Date of Test				2/9/1909		2/9/1909		2/10/1909	
Gauge Number	Diameter of Main Inches	Distance from Entrance to Tunnel Ft.	Steam Passing per Hour Pounds	Approximate Velocity of Steam Ft. per Sec.	Gauge Pressure Lbs. per Sq. Inch	Approximate Velocity of Steam Ft. per Sec.	Gauge Pressure Lbs per Sq. Inch	Approximate Velocity of Steam Ft. per Sec.	Gauge Pressure Lbs. per Sq. Inch
1	10	0	25920	238	7.25	191	13.0	213	10.0
2	10	633.5	22600	225	5.4	186	10.0	193	7.6
3	10	1060	9410	103	3.6	81	8.7	95	5.1
4	10	1481	5300	59	3.2	46.2	8.5	55	4.7
5	10	2079	2180	23.1	4.1	18.3	9.4	20.4	6.8
6	9	1072	9950	135	3.8	86	8.7	100	5.4
7	10	1455	4890	51	4.4	41.6	9.1	47.6	5.9
8	10	1853	1440	15.2	4.25	12.3	8.95	14.3	5.5

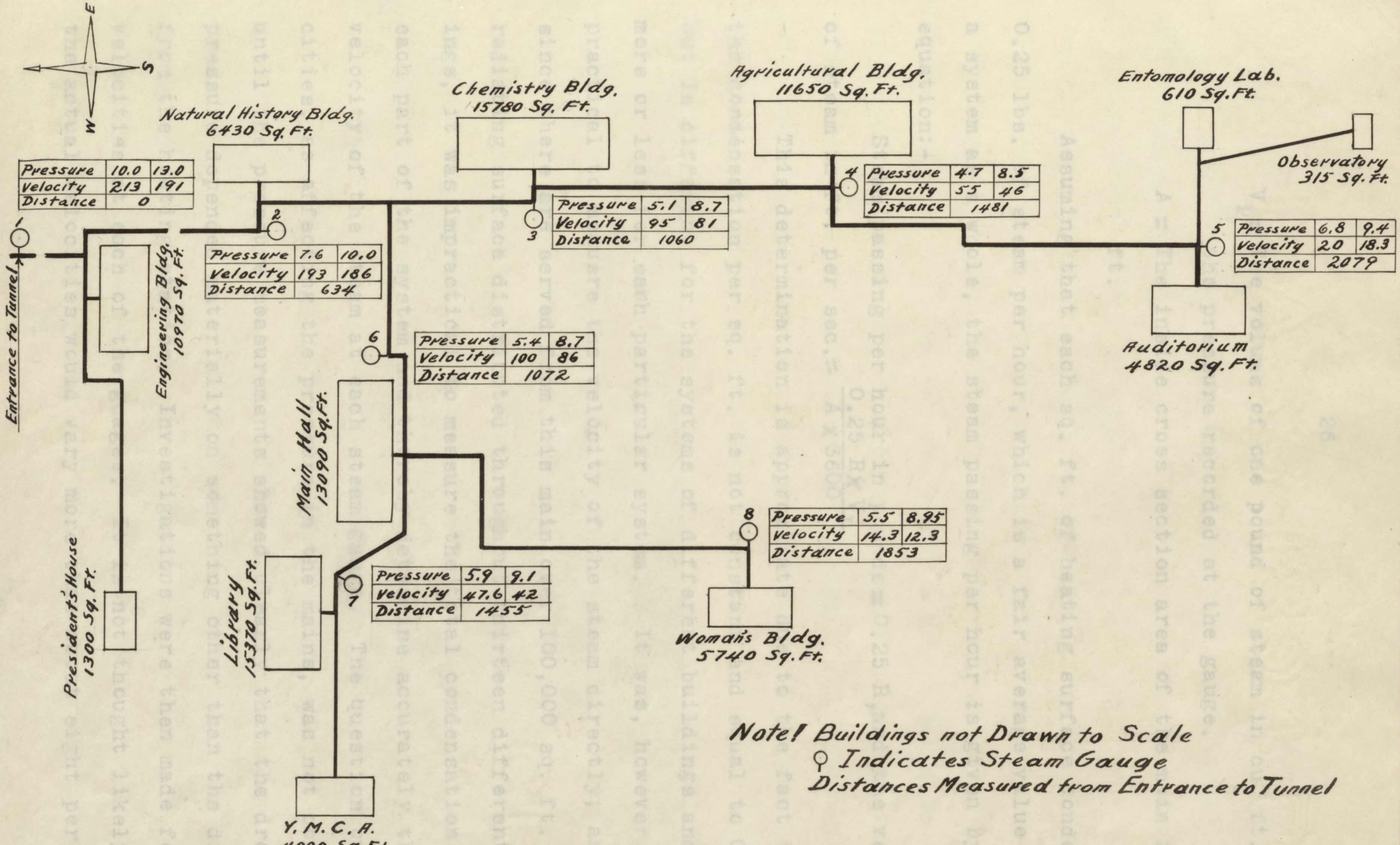


FIGURE 2

LOCATION OF GAUGES, DISTRIBUTION OF HEATING SURFACE AND FALL OF PRESSURE

Scale 1" = 200 Ft.

V_p = The volume of one pound of steam in cu. ft. at the pressure recorded at the gauge.

A = The inside cross section area of the main in sq. ft.

Assuming that each sq. ft. of heating surface condenses 0.25 lbs. of steam per hour, which is a fair average value for a system as a whole, the steam passing per hour is given by the equation:-

Steam passing per hour in pounds = 0.25 R, and the velocity of steam in ft. per sec. = $\frac{0.25 R \times V_p}{A \times 3600}$.

This determination is approximate due to the fact that the condensation per sq. ft. is not constant and equal to 0.25 but is different for the systems of different buildings and varies more or less for each particular system. It was, however, impractical to meausre the velocity of the steam directly; and, since there are served from this main over 100,000 sq. ft. of radiating surface distributed throughout thirteen different buildings, it was impractical to measure the total condensation for each part of the system and thereby determine accurately the velocity of the steam at each steam gauge. The question of velocities, as affecting the pressure in the mains, was not considered until the pressure measurements showed clearly that the drop in pressure depended materially on something other than the distance from the heating station. Investigations were then made for the velocities at each of the guages. It is not thought likely that the actual velocities would vary more than about eight per cent from the calculated values.

Significance of Results:- These results indicate that in far reaching heating systems in which the service is taken off in large units, if the service mains are taken off the side of the main in the usual manner, there is less danger of the pressure being too low at the end of the line than farther back where the steam has greater velocity. This would be especially noteworthy in very large systems where the desire to avoid the cost of very large mains would result in the installation of mains in which the velocity is above normal. Several illustrations of the rise in pressure at the end of the mains can be found in Fig. 2. At the Agricultural Building the pressure is lower than at the gauge 600 ft. farther out. Again, at the gauge just "before" Main Hall the pressure is lower than at the Library, 280 ft. farther out, or at the Woman's Building which is 780 ft. farther out. Table 7 shows that this increase of pressure at the terminals occurs in all of the tests. These gauges were all carefully calibrated with the same gauge tester and some of them were exchanged during the third test.

Since the drop in pressure depends upon the velocity more than the distance from the heating station, where it is desirable to keep the pressure nearly constant, it would seem advantageous to so arrange the service connections that the inertia of the moving steam will not tend to decrease the pressure. If the service connections were arranged something like the service to the radiators in a building is arranged to insure the steam entering all of the radiators, it would probably effect the desired result.

LOSS BY CONDENSATION IN MAINS

Object of Tests:- The object of these tests was to determine the amount of heat lost from low-pressure steam mains when covered with a good standard pipe covering and when carrying steam at the ordinary low pressures.

METHOD OF PROCEDURE

Description of System:- The mains used for these tests embrace the entire low pressure mains in the South tunnel at the University of Illinois, except the underground main leading from the Library to the Y. M. C. A. building. A rough map of this tunnel system is given in Fig. 2 in the discussion of the loss of pressure. All the mains drain toward three points, viz., the Agricultural Building, to which drain all the mains beyond this point; the second turn beyond Main Hall in the Woman's Building tunnel, to which drain all the mains beyond the first turn in the same tunnel; the entrance to the tunnel, to which drain all the rest of the mains tested. At these points the condensed steam is trapped out of the mains and is run into the return mains.

Arrangements for Testing:- Because the system was thus divided up, and because of the fact that there were not men and apparatus enough to conduct tests at all these places at the same time, what should have been one test of the entire system was divided into three tests. At the points toward which the mains drain the connections from the traps to the return mains were broken and connections were made from the traps to tanks containing cold water and supported upon scales for weighing the condensed steam. While testing a part of the mains the steam was cut off from all the buildings on that part in order to prevent the moving steam from carrying the water through with it. The steam pressure and the moisture in the steam were measured at the entrance to the portion tested, the former by means of a low pressure steam gauge and the latter by means of a separating calorimeter.

Probability of Inaccuracy:- The probability of the condensation, determined in this way, varying materially from the condensation when the steam is in motion is believed to be but slight.

RESULTS

The results of these tests are given in table 8. The considerable lenght of time between the different tests was allowed to elapse because the heat could not be shut off from the buildings at all times, and, consequently, a test could not be made except on a bright warm day.

Significance of Results:- The mains of 4" diameter and smaller are laid under ground in tiling packed with magnesia. The percentage of the main surface that is laid under ground,

TABLE 8 - CONDENSATION IN LOW-PRESSURE STEAM MAINS

	Part of System Tested	From Agricultural Bldg. to Auditorium, to Entomology Lab. and to Observatory	From 1st Turn west beyond Main Hall to Woman's Building	All Remainder of South Tunnel Mains Except from Library to Y.M.C.A. & from Eng. H. to Pres. H.	Totals and Averages with Each Test Weighted according to Area of Surface Tested
(1)	Date of Test	2/19/1909	2/23/1909	11/10/1909	
(2)	Duration of Test, Hrs.	5	5	5	
(3)	Mean Steam Pressure, Lbs per Sq. in. Gauge	7.2	8.8	9.6	9.0
(4)	Mean Temperature of Entering Steam, °F	232.8	236.6	238.5	236.0
(5)	" " of Tunnel, °F	80 (Approx)	85	101	94.6
(6)	" " of Condensed Steam, °F.	208	212	211.5	211.1
(7)	Total Steam Condensed, Lbs.	1214	565	2758	4537
(8)	Same per Hour, Lbs.	242.8	113	551.6	905.4
(9)	Moisture in Steam	.042	.018	.060	.051
(10)	Total Heat in 1 lb. of Moist Steam, B.t.u.	1112.6	1137	1097.9	1106.4
(11)	Heat Lost by 1 lb. of Steam, B.t.u.	935.8	956.1	917.5	926.7
(12)	Total Heat Lost per Hour, B.t.u.	227210	108040	506093	841343
(13)	Equivalent Condensation per Hr. at & to 212°F. Lbs	235.3	111.9	524.1	871.2
(14)	Horse Power Consumed	6.82	3.24	15.19	25.25
(15)	Nominal Diameter of Mains Tested, Inches	10 / 6 / 4 / 2.5	10 / 6	10 / 9 / 6	10 / 9 / 6 / 4 / 2.5
(16)	Length of Mains Tested, Ft.	591.5 / 14 / 116 / 220	512.5 / 25.5	1930 / 380 / 225	3034 / 380 / 264.5 / 116 / 220
(17)	Thickness of Pipe Covering, Inches	$1\frac{3}{8}$ / $1\frac{3}{16}$	$1\frac{3}{8}$ / $1\frac{3}{16}$	$1\frac{3}{8}$ / $1\frac{3}{8}$ / $1\frac{3}{16}$	
(18)	Kind of Covering, Material	Magnesia / Magnesia in Tile	Magnesia	Magnesia	
(19)	Surface Area of Mains Tested, Sq. Ft.	2030	1488	6790	10308
(20)	B.t.u. Lost per Hr. per Sq. Ft. of Covered Main Surface	111.9	72.6	74.5	81.6
(21)	Same per Degree Diff. Temp. of Steam & Surrounding Air.	.73	.48	.54	.57

however, is small and the results here derived should represent fairly well the heat lost from the low pressure mains in tunnels. The value of 0.57 B.t.u. lost per hour, per sq. ft. of covered main surface per degree diff. temp. between steam and surrounding air is about 25 per cent of that lost by uncovered wrought iron pipes under the same conditions and about 35 per cent of the corresponding radiation factor for ordinary cast iron radiators.

LOSS FROM RETURN MAINS

Another loss which must be considered is the loss of heat from the condensed steam in the return mains. The total surface of the return mains in this part of the system is 5540 sq. ft. The pipes range from 1" to 4" in diameter, about 88 per cent of the surface being that of 4" pipes. All of this surface is covered with 85 per cent magnesia covering, which allows about 0.75 B.t.u. to escape per sq. ft. per hour per degree difference between the temperatures of the water inside and the air of the tunnel. This temperature difference averages about 100°F. Hence the heat emitted per sq. ft. of return main surface per hour is about 75 B.t.u. While this value depends to some extent upon the amount of steam being used and becomes almost zero in summer when only the condensed steam from the steam mains is passing through the returns, it may be taken as constant for the heating season without sensible error, so that the heat lost from the return mains per hour is $q_h = 5540 \times 75 = 415500$ B.t.u.

RATIO OF HEAT LOST IN MAINS TO TOTAL HEAT SUPPLIED

The ratio of the heat lost in the mains to the total heat supplied depends largely upon the percentage of the time that the steam is turned on in the buildings served. This ratio may be calculated as follows:-

Let $(S_1, S_2, \text{---} S_u)$ = Heating surface of u buildings served.

$(M_1, M_2, \text{---} M_u)$ = Number of hours each building is served during the period in question.

N = Number of hours in such period.

dT = Average difference temp. steam and room.

R = B.t.u. transmitted per hour per sq. ft. heating surface per degree diff. temp. steam and room.

Q = Heat lost from steam mains per hr., B.t.u.

$q = q_h \times N$ = Heat lost from return mains during this period, B.t.u.

C = Percentage loss

In general this gives the equation:-

$$C = \frac{(QN + q)}{(S_1 M_1 + S_2 M_2 + \text{--} S_u M_u)\, RdT + (QN + q)}$$

as average values for R and dT we may take:-

$R = 1.6$
$dT = 160$ and $RdT = 256$

$$\text{Hence } C = \frac{QN + q}{256\,(S_1 M_1 + S_2 M_2 + \text{---} S_u M_u) + (QN + q)}$$

For the percentage loss when all the buildings are heated during the entire period we have:-

$M_1 = M_2 = --M_u = N$ which we may take $= 1$

Then $$C' = \frac{Q + q}{256\,(S_1 + S_2 + --S_u) + Q + q}$$

These are the values for the total loss in the tunnel. For the losses in the steam and return mains taken separately, we have:-

For steam mains,-

Any condition -

$$C_Q = \frac{QN}{256\,(S_1 M_1 + S_2 M_2 + --- S_u M_u) + QN + q}$$

All buildings on,-

$$C'_Q = \frac{Q}{256\,(S_1 + S_2 + ---S_u) + Q + q}$$

For Return Mains,

Any Condition,-

$$C_q = \frac{q}{256\,(S_1 M_1 + S_2 M_2 + --- S_u M_u) + QN + q}$$

All buildings on,-

$$C'_q = \frac{q}{256\,(S_1 + S_2 + ---S_u) + Q + q}$$

In table 9 are given the calculated values of C', C_Q' and C_q' ; the values of C, C_Q and C_q for different periods of and the entire year are likewise tabulated. Values of M_1, M_2---

M_u were recorded for the entire heating season of 1908-1909 except for one week in February which week has been discarded in calculating all results. As the steam is left on the mains during the entire year, it will be noticed that the percentage loss is considerably greater for the entire year, as well as for those months when the weather is not severe, than for the cold months. Only in January does the loss approximate closely to that when the entire plant is in operation. This approximation would be much closer for a severe winter, the winter in question having been a very mild one. Values of C'_Q, C'_q and C' decrease with an increase in the ratio of the heating surface served to the surface of the mains and returns, while the values C_Q, C_q and C approximate more closely those of C'_Q, C'_q and C' as the percentage of the time during which the buildings are heated increases.

TABLE 9- PERCENTAGE OF HEAT SUPPLIED TO SYSTEM THAT IS LOST IN MAINS FOR DIFFERENT PERIODS.

C'_Q = Percentage Loss in Steam Mains when All Buildings are on	C'_q = Percentage Loss in Return Mains When all Buildings are on	$C' = C'_Q + C'_q$
3.41	1.58	4.99

Period	C_Q = Percentage Loss in Steam Mains, Running Conditions	C_q = Percentage Loss in Return Mains, Running Conditions	C = Total percentage Loss in Steam and Return Mains, Running Conditions
October	8.71	4.05	12.76
November	6.09	2.82	8.91
December	5.35	2.49	7.84
January	4.71	2.18	6.89
February	5.40	2.51	7.91
March	5.41	2.52	7.93
April	6.47	3.00	9.47
Entire Heating Season	5.86	2.72	8.58
Entire Year	9.87	2.82	12.69

The losses given in table 9 are very high due to the facts that the winter was very mild as stated above and that the buildings are separated by considerable distances. Since these losses were determined two new systems have been added, viz. those of the Physics building and the Natural History Addition. The direct surface equivalent of these two systems is about 27010 sq. ft. making a total of 125,635 sq. ft. for the portion of the system served from the South Tunnel mains. If we assume the same heating schedule as for the winter of 1908-1909, the values of C'_Q, C'_q and C' and the Values of C_Q, C_q and C for the total heating season and for the entire year are as shown in table 9A.

TABLE 9A- PERCENTAGE OF HEAT SUPPLIED TO SYSTEM THAT IS LOST IN MAINS

	$C'_Q = 2.70$	$C'_q = 1.26$	$C' = 3.96$
Period	C_Q	C_q	C
Total Heating Season	4.84	2.25	7.09
Entire Year	8.22	2.35	10.57

But little data is available on the usual value of this loss. Mr. James O. White in Bulletin 110 of the American District Steam Company on the results secured by the Citizen's Light, Heat and Power Company of Johnstown, Pa., from the operation of the Central Heating System operated in connection with their Vine Street Power Station, states that the average loss by condensation in about 2 1/2 miles of street mains does not exceed 5 per cent. It appears that the total loss from well covered steam and return mains should not exceed 5 per cent where the buildings are comparatively close together as in business blocks etc., and is less than 10 per cent in almost all cases.

LOSS FROM BOILER AND GRATE.

This loss has been treated by so many authors that it is not necessary to go into details here in regard to general cases. The combined efficiency of the boiler and grate ranges usually between 50 and 75 per cent. This means that from 25 to 50 per cent of the heating value of the fuel is lost during the evaporation of the feed water into steam. The magnitude of this loss depends on many minor factors which may be summed up under three main heads as follows:- The efficiency of the plant equipment, the kind and condition of the fuel, and the competency of the operating force. In table 10 are given values of the boiler and grate efficiency during a number of trials of the boilers in the Central Heating Station at the University of Illinois. In the

TABLE 10—RESULTS OF BOILER TRIALS AT THE CENTRAL HEATING STATION OF THE UNIVERSITY OF ILLINOIS SHOWING THE AVERAGE EFFICIENCY AND COST OF COAL FOR EVAPORATING 1000 POUNDS OF WATER INTO DRY STEAM FROM & AT 212°F.

A.S.M.E. Code Number	Test Number		1	2	3	4	5	6	7	8	9	10	Average	Average for old Tests
	Kind of Furnace		Stirling	Stirling	Stirling	Stirling	National	National	National	National	2 B.&W., 2 Stir., 1 Nat.	3 Stirling 1 National		
	Kind of Furnace		Chain Grate	Chain Grate	Chain Grate	Chain Grate	Chain Grate	Chain Grate	Chain Grate	Chain Grate	Chain Grate	Chain Grate	Chain Grate	Chain Grate
	Plant Number of Boiler		7 & 8	7	7	7	4	4	4	4	1,2,3,4,7	3,4,7,8	1,2,3,4,7,8	Entire Plant
	Type of Boiler		Water Tube	Water Tube	Water Tube	Water Tube	Water Tube	Water Tube	Water Tube	Water Tube	Water Tube	Water Tube	Water Tube	Water Tube
	Kind of Fuel		From Danville Electric Mine											
1	Date of Trial		10/24/08	10/26/08	10/27/08	10/28/08	12/4/08	12/7/08	12/8/08	12/9/08	1/2/09	1/9/09	10/24/08—1/9/09	12/22/03—4/13/07
2	Duration of Trial, Hrs		8.75	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	9.3
3	Grate Surface Area, Sq. Ft.		51.5 Each	51.5	51.5	51.5	59.0	59.0	59.0	59.0	218.5	220.5		376.9
7	Water Heating Surface, Sq. Ft.		2609 Each	2609	2609	2609	2513	2513	2513	2513	10703	10340		18102
11	Mean Steam Pressure, Gauge, lbs per Sq. in.		121.5	136.0	139.6	143.9	138.2	134.6	141.1	142.2	142.6	142.5	138.2	125.3
12	Force of Draft between Damper & Boiler, ins. Water		0.41	0.21	0.18	0.29	0.31	0.34	0.30	0.33	0.73	0.74	0.38	0.38
20	Temperature of Feed Water Entering Boiler, °F.		115	136	141	137	143.8	153.7	150.4	164.7	160	158.8	146	91.4
21	Temperature of Gases Escaping from Boiler, °F		573	664	650	657	599	609	585	591	562		610	
23	Size and Condition of Fuel		1¼ inch Screenings, Containing a Large Percentage of Dust											Principally Pea Coal
27	Total Weight of Dry Coal Consumed, lbs.		19755	13082	13130	16245	15686	15745	15453	15352	51017	58888		
31	Ash and Refuse in Dry Coal, Percent		21.50	21.85	27.14	25.60	21.55	26.59	27.13	19.48	26.38	23.10	24.03	17.48
32	Proximate Analysis of Coal	Fixed Carbon												42.18
33		Volatile Matter												33.87
34		Moisture	12.42	11.75	12.47	12.44	12.44	13.25	11.95	12.44	13.66	11.38	13.02	10.45
35		Ash	18.15	15.61	17.22	17.06	17.06	17.89	20.60	17.06	15.43	15.71	17.18	13.49
36		Sulphur, Separately Determined	4.40	3.71	4.17			4.16	4.80		3.77	4.13	4.16	1.56
48	Dry Coal Consumed per Sq. Ft. of Grate Surface per Hr., lbs		21.9	25.4	25.5	27.6	26.6	26.7	26.2	26.0	23.3	26.7	25.6	22.7
50	B.t.u. per Pound of Dry Coal		11247	11808	11479	11460	11460	11400	10921	11460	11782	11429	11445	11838
54	Moisture in the Steam, Percent.		1.14	0.92	1.22	1.04	1.09	1.06	1.10	1.02	1.04	1.05	1.07	1.83
59	Water Evaporated Corrected for Quality of Steam, lbs		141487.3	74960.1	78470.3	82610.2	86661.1	87584.5	81226.6	85912.2	330285	358672		
64	Equivalent Evaporation per Hr. from & at 212 °F. per Sq. Ft. of Water Heating Surface, lbs.		3.55	3.24	3.37	3.57	3.86	3.85	3.59	3.74	3.40	3.82	3.60	3.41
65	Horse Power Developed		536.75	244.65	254.97	269.60	280.90	280.55	261.60	272.50	1055.0	1146.8		
66	Builder's Rated Horse Power		520	260	260	260	250	250	250	250	1070	1030	1330	1770
67	Percentage of Builder's Rated Horse Power Developed		103.2	94.1	98.1	103.7	112.4	112.2	104.6	109.0	98.6	111.3	104.7	102.5
70	Equivalent Evaporation from & at 212 °F. per lb. of Dry Coal, lbs		8.20	6.45	6.70	6.54	6.18	6.15	5.84	6.12	7.13	6.72	6.60	7.64
73	Efficiency of Boiler and Grate, Percent.		70.40	52.77	56.36	55.11	52.03	52.07	51.60	51.60	58.44	56.76	57.40	62.20
74	Cost of coal per Ton of 2000 lbs. Delivered in Boiler Room, $—		1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	
76	Cost of Fuel for Evaporating 1000 lbs. of Water F. & A. 212°, $—		0.0967	0.108	0.105	0.108	0.114	0.115	0.120	0.115	0.100	0.103	0.102	
84	Carbon Dioxide in Flue Gas, Percent		3.6	7.5	7.3	8.1	3.7	3.1	4.0	4.3	5.1	5.8	5.3	9.1

majority of these tests the efficiency was doubtless considerably lower than it would have been with a good grade of coal. In this table there is also given the cost of evaporating 1000 pounds of water into dry steam from and at 212°F.

CHAPTER III.

COST OF COAL FOR SUPPLYING HEAT

Object:- The object of this discussion is to present a method by which the cost of coal for supplying heat from any central heating station may be determined.

Nature of Work:- This presentation consists of the necessary formulas, with their derivation; sufficiently elaborate data in the form of tables and curves to cover all ordinary cases; explanation of these tables and curves and the solution of one or more problems for the purpose of illustration.

COST OF COAL PER SQ. FT. OF HEATING SURFACE PER ANNUM

Derivation of Formula:- A unit of heat which is used in boiler performance, and which it is very convenient to use here, is the heat required to evaporate 1000 lbs. of water into dry steam from and at 212° F. It is equivalent to 965,700 B.t.u.

Let H = Heating value of one lb. of coal as fired, B.t.u.

K = Cost of one ton of coal of 2000 lbs., \$ –

E = Efficiency of Boiler and Grate, per cent

M = Thousands of lbs. of water evaporated into dry steam from and at 212°F. per ton of coal as fired.

k = Cost of evaporating 1000 lbs. of water into dry steam from and at 212° F, \$ –

$$\text{Then } M = \frac{H \times E}{100} \times \frac{2000}{965700} = \frac{E \times H}{48285}$$

and $k = \frac{K}{M} = \frac{48,285\ K}{EH}$ = cost of supplying 965,700 B.t.u. to the heating mains.

Table 11, gives values of M for boiler efficiencies ranging from 40 per cent to 75 per cent and for the ordinary heating values of coals. On chart I, the straight line curves represent the values of M for these different values of E and H, to the scale on the left of the chart. By interpolation between these curves, values of M for coals of any heating value between 9000 and 14,000 B.t.u. per pound as fired can be found.

Table 12, gives values of k for the same range of boiler efficiency and the same heating value of coals, with coal costing $1.00 per ton of 2000 lbs. The curved lines on chart 2 represent these values of k to the scale on the left of the chart. The cost of coal for evaporating 1000 lb. of water into dry steam with coal at any price is found by multiplying the value of k from the scale on the left by the cost of coal per ton in dollars. In this case also values may be found by interpolation when the heating value of coal lies between two curves.

Heat required per sq. ft. Heating Surface:-

Let F = B.t.u. emitted per sq. ft. heating surface per hour per degree difference between temperature steam and room.

dT = Degrees difference between temperatures of steam and room.

$Q = F \times dT$ = B.t.u. emitted per sq. ft. heating surface per hour.

TABLE 11 - THOUSANDS OF POUNDS OF WATER EVAPORATED INTO DRY STEAM FROM AND AT 212°F. PER TON OF COAL AS FIRED

E	Calorific Value of Fuel, B.t.u, H									
	9000	9500	10000	10500	11000	11500	12000	12500	13000	14000
40	7.46	7.87	8.28	8.70	9.11	9.53	9.94	10.36	10.77	11.60
45	8.39	8.85	9.32	9.78	10.25	10.72	11.18	11.65	12.12	13.05
50	9.32	9.84	10.36	10.87	11.39	11.91	12.43	12.94	13.46	14.50
55	10.25	10.82	11.39	11.96	12.53	13.10	13.67	14.24	14.81	15.95
60	11.18	11.81	12.43	13.05	13.67	14.29	14.91	15.53	16.15	17.40
65	12.12	12.79	13.46	14.13	14.81	15.48	16.15	16.83	17.50	18.85
70	13.05	13.77	14.50	15.22	15.95	16.67	17.40	18.12	18.85	20.30
75	13.98	14.76	15.53	16.31	17.09	17.86	18.64	19.42	20.19	21.75

TABLE 12 - COST OF EVAPORATING 1000 POUNDS OF WATER INTO DRY STEAM FROM AND AT 212°F. WHEN PRICE OF COAL = \$1.00 PER TON OF 2000 Lbs.

E	Calorific Value of Fuel, B.t.u									
	9000	9500	10000	10500	11000	11500	12000	12500	13000	14000
40	\$0.134	\$0.127	\$0.121	\$0.115	\$0.110	\$0.105	\$0.101	\$0.097	\$0.093	\$0.086
45	.119	.113	.107	.102	.098	.093	.089	.086	.083	.077
50	.107	.102	.097	.092	.088	.084	.081	.077	.074	.069
55	.098	.092	.088	.084	.080	.076	.073	.070	.068	.063
60	.089	.084	.081	.077	.073	.070	.067	.064	.062	.058
65	.083	.078	.074	.071	.068	.065	.062	.059	.057	.053
70	.077	.073	.069	.066	.063	.060	.058	.055	.053	.049
75	.072	.068	.064	.061	.059	.056	.054	.052	.050	.046

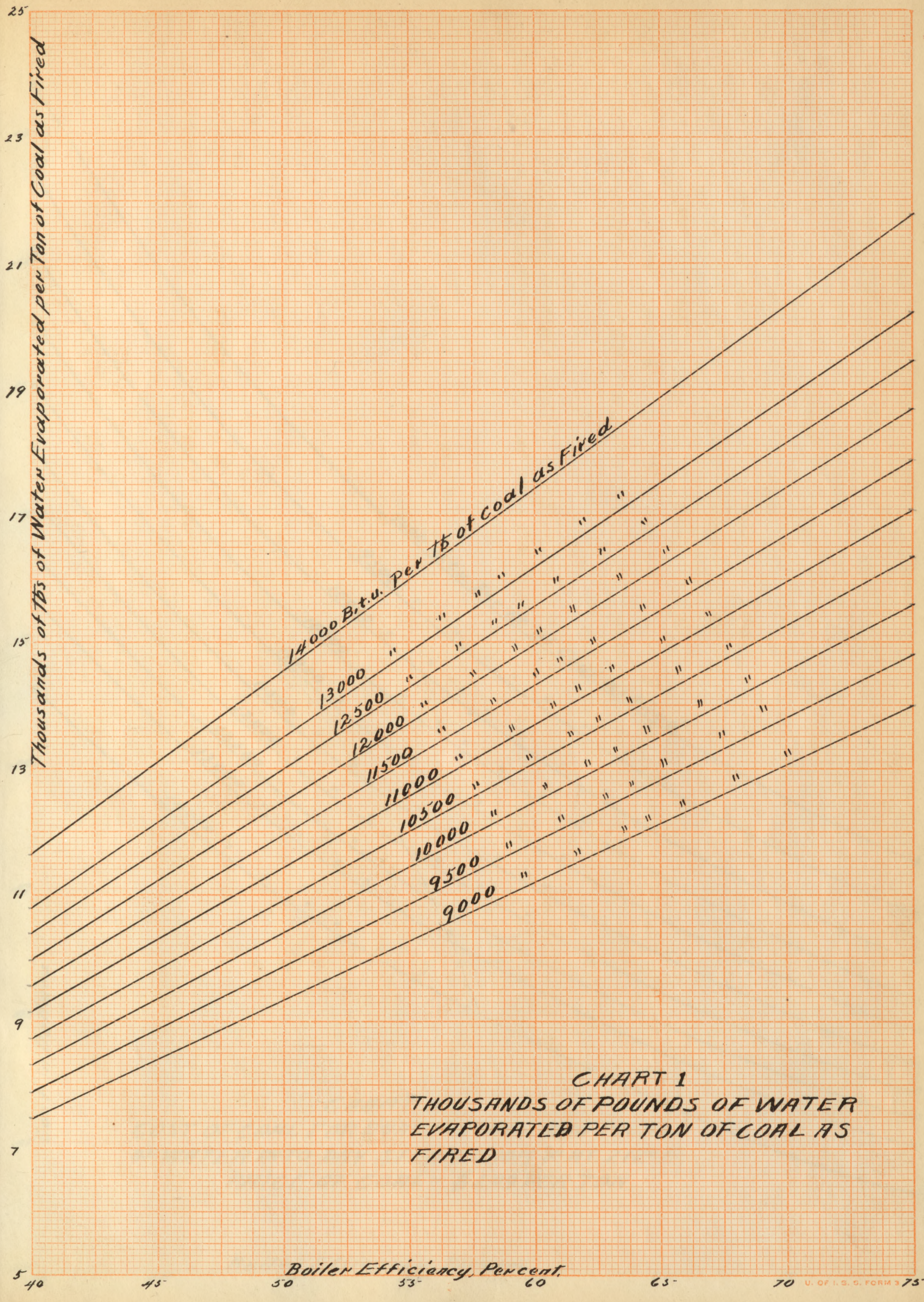


CHART 1
THOUSANDS OF POUNDS OF WATER EVAPORATED PER TON OF COAL AS FIRED


.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
Cost in Dollars
40
45
50
55
60
65
70
75
Boiler Efficiency, Percent.
9000 B.t.u. Per lb. of Coal as Fired
9500 "
10000 "
10500 "
11000 "
11500 "
12000 "
12500 "
13000 "
14000 "
CHART 2
COST OF COAL FOR EVAPORATING 1000 POUNDS
OF WATER INTO DRY STEAM FROM & AT 212° F.
PRICE OF COAL = $1.00 PER TON
U. OF I. S. S. FORM 3

n_1 = Number of hours any building is heated per day.

n_2 = Number of days same building is heated per year.

C = Percentage of heat supplied from boiler lost in mains.

h = B.t.u. required at boiler to furnish steam to one sq. ft. of heating surface for any period.

Then $$h = \frac{Q \times n_1 \times n_2}{\left(1 - \frac{c}{100}\right)}$$

(Note! For any heating period, however, short, n_2 is always equal to or greater than unity, i.e., $n_2 \geqq 1$)

Table 13, gives values of Q for different values of F and dT, the latter depending entirely on the steam pressure when the room temperature is taken as constant and equal to 70° F. as has been done in this case. On Chart 3 the straight line curves represent these values of Q to the scale on the left. Interpolation may be used to find approximate values for other steam pressures.

In table 14 are given values of h for the same values of F and the same steam pressures and for values of C from 5 to 15 per cent when n_1 and n_2 are each equal to unity. The straight line curves on charts 4--8 inclusive represent these values of h to the scale on the left. The same curves represent values of h for $n_1 = 10$, $n_2 = 1$ to the second scale from the left; for $n_1 = 10$, $n_2 = 200$ to the third scale from the left; for $n_1 = 24$, $n_2 = 1$ to the fourth scale and for $n_1 = 24$, $n_2 = 200$ to the last scale on the

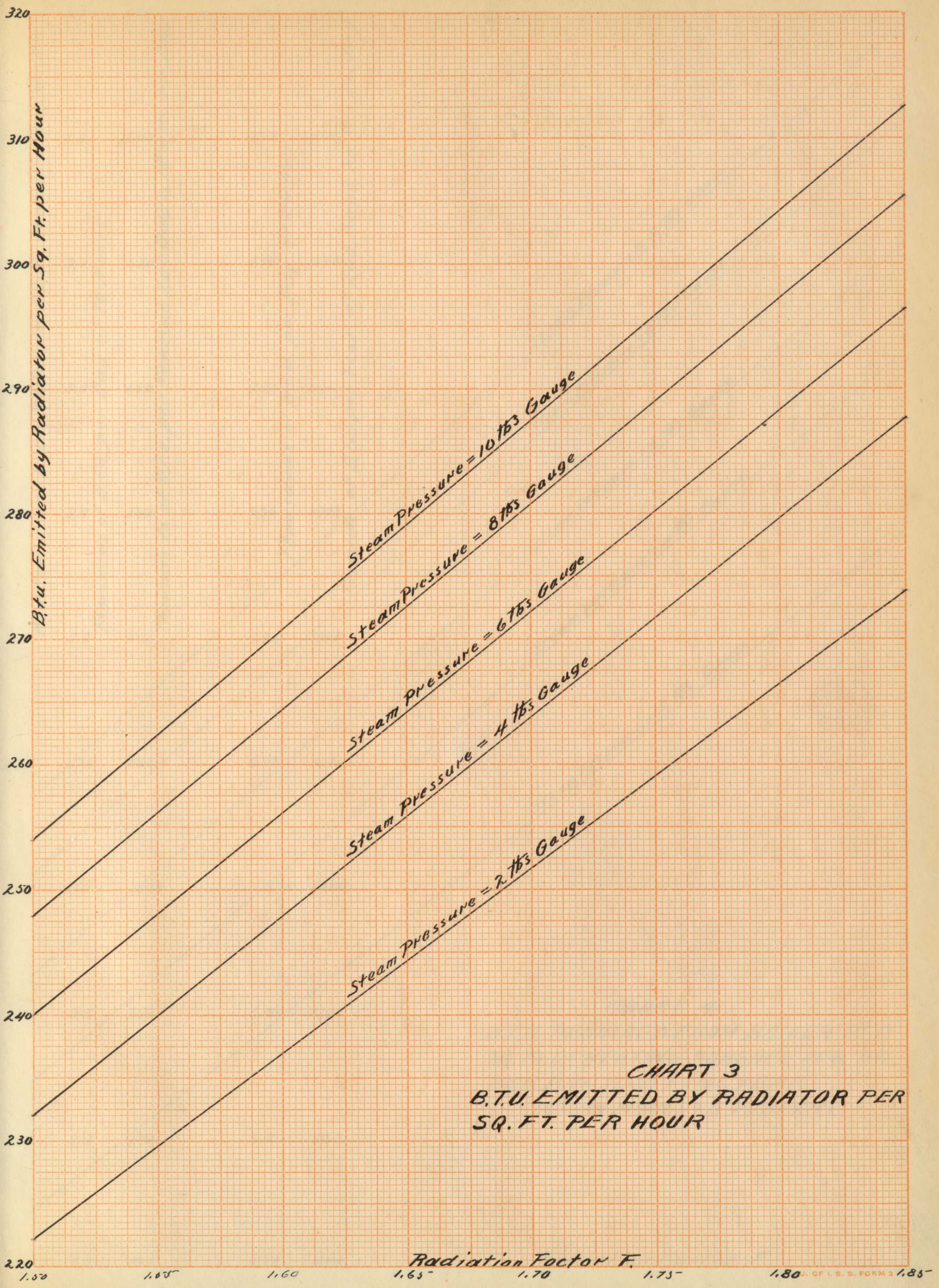


CHART 3
B.T.U. EMITTED BY RADIATOR PER SQ. FT. PER HOUR

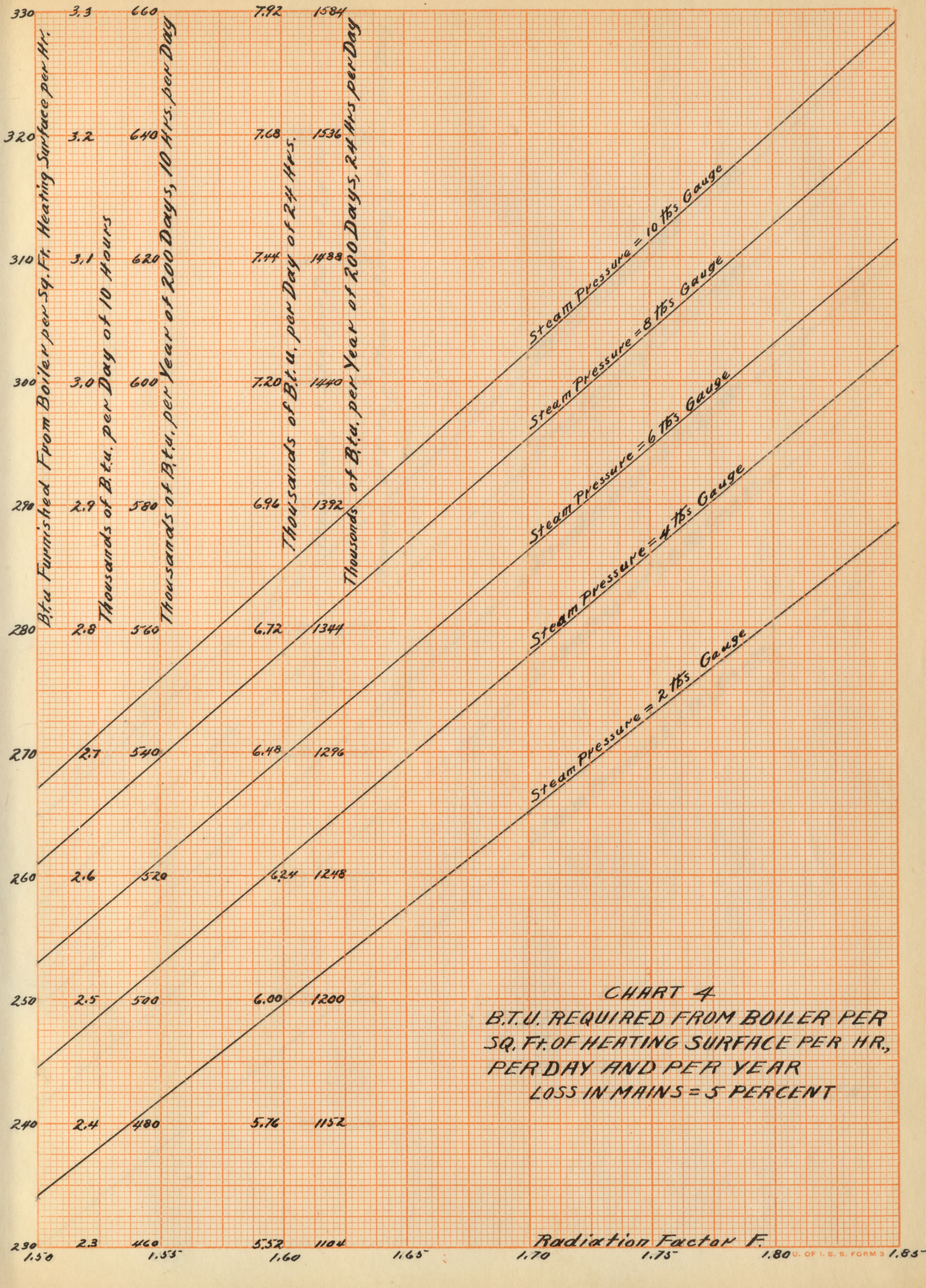


CHART 4
B.T.U. REQUIRED FROM BOILER PER SQ. Ft. OF HEATING SURFACE PER HR., PER DAY AND PER YEAR
LOSS IN MAINS = 5 PERCENT

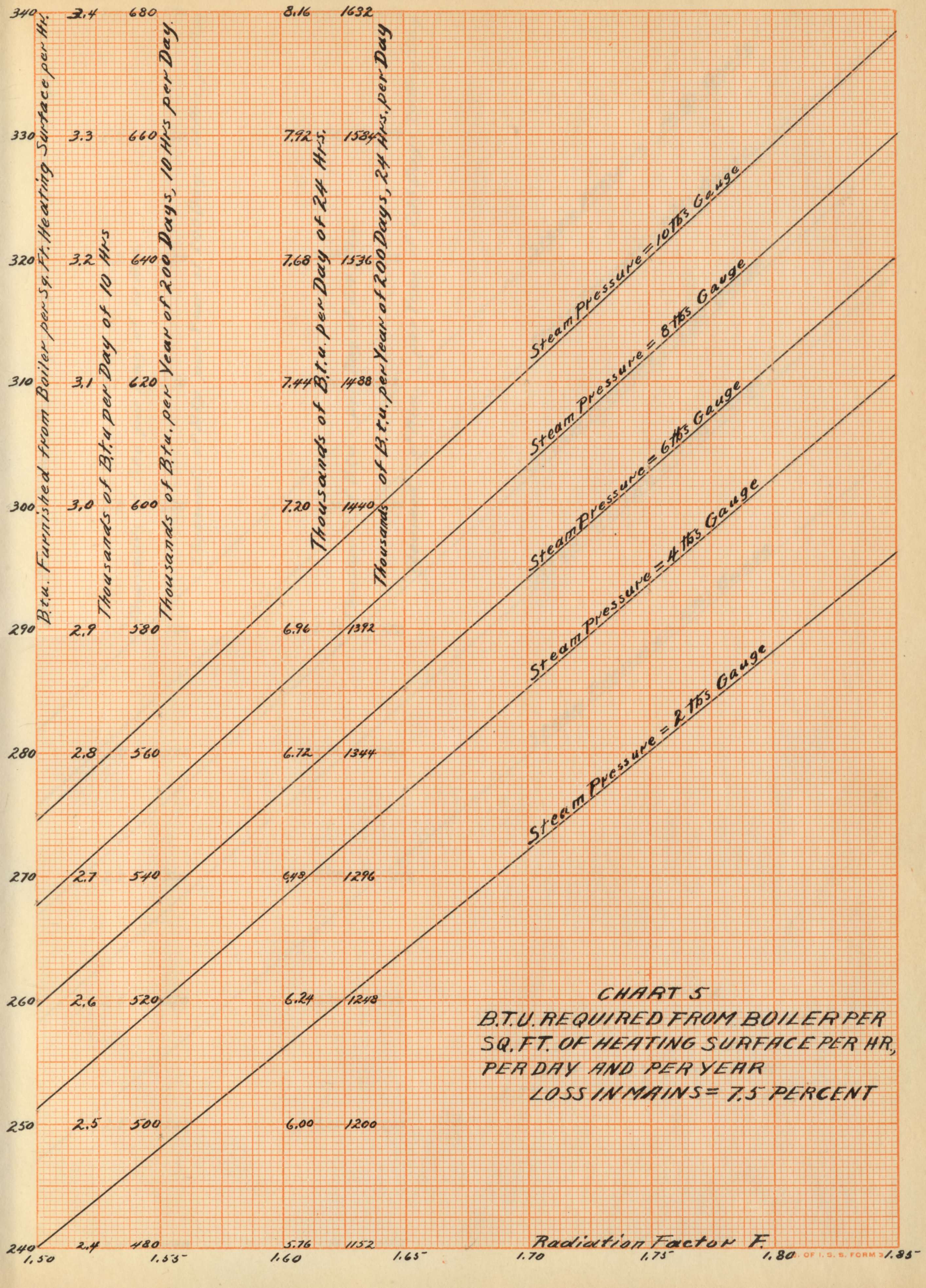


CHART 5
B.T.U. REQUIRED FROM BOILER PER SQ. FT. OF HEATING SURFACE PER HR, PER DAY AND PER YEAR
LOSS IN MAINS = 7.5 PERCENT

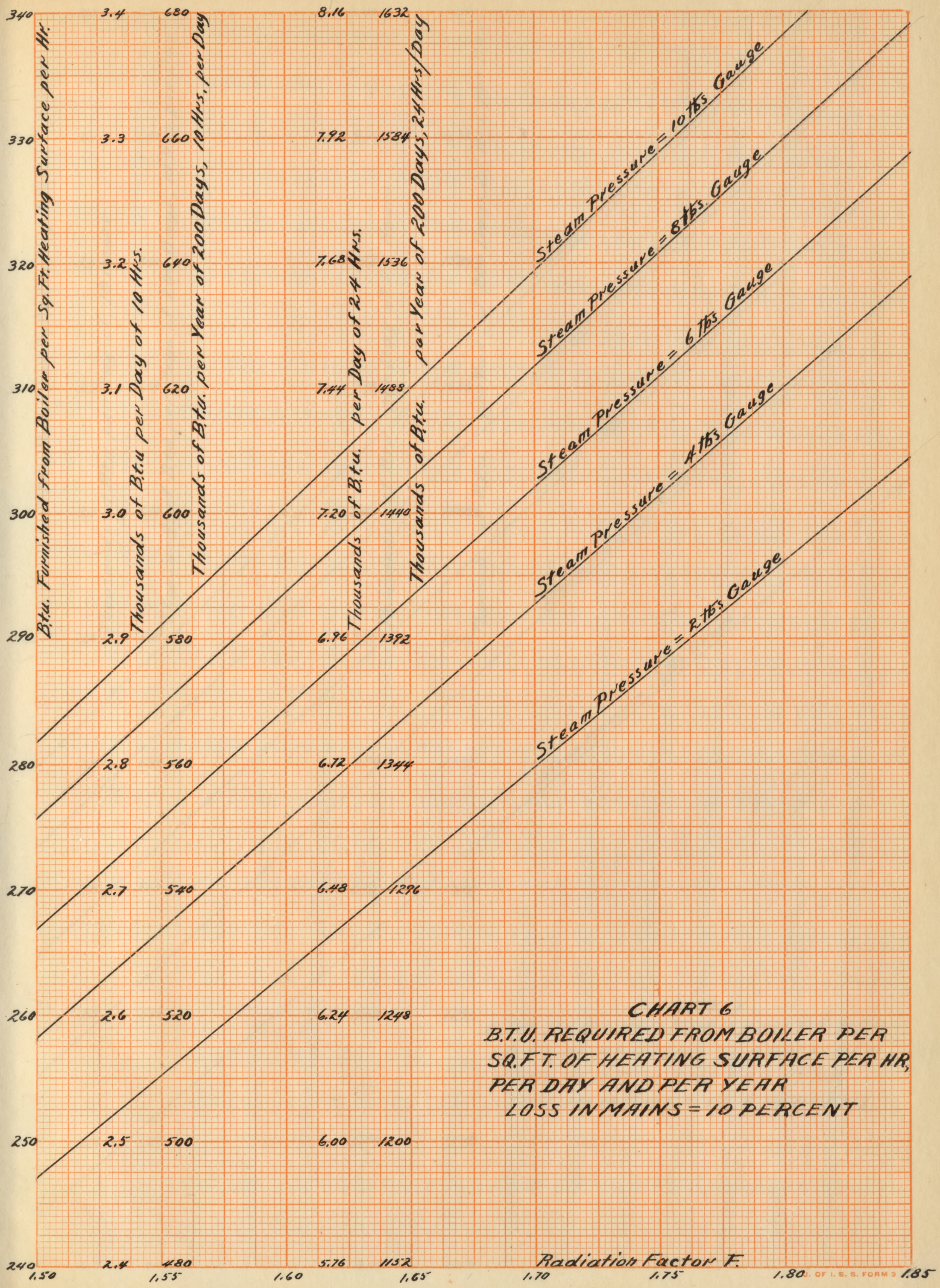


CHART 6
B.T.U. REQUIRED FROM BOILER PER SQ.FT. OF HEATING SURFACE PER HR, PER DAY AND PER YEAR
LOSS IN MAINS = 10 PERCENT

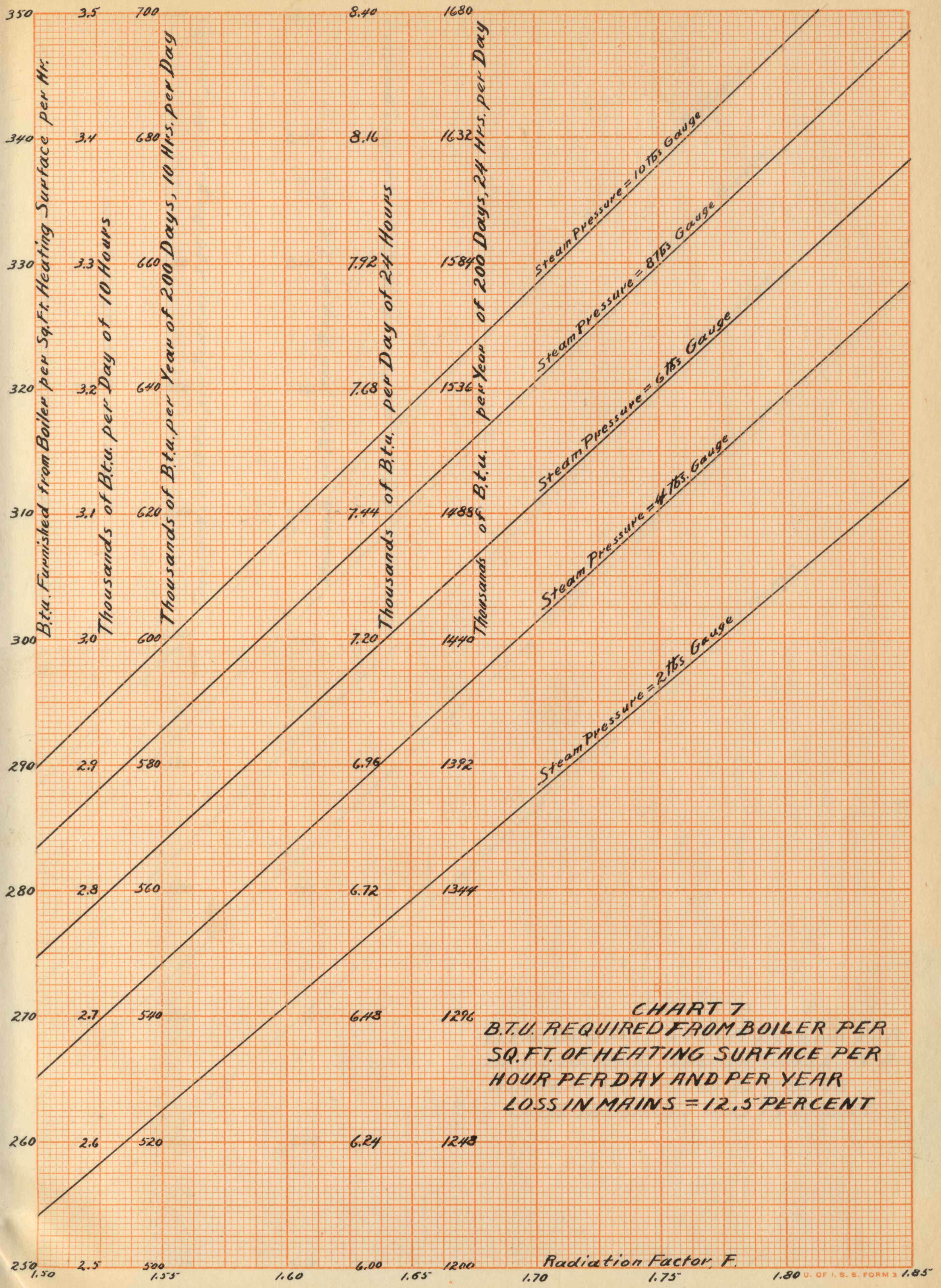


CHART 7
B.T.U. REQUIRED FROM BOILER PER SQ. FT. OF HEATING SURFACE PER HOUR PER DAY AND PER YEAR
LOSS IN MAINS = 12.5 PERCENT

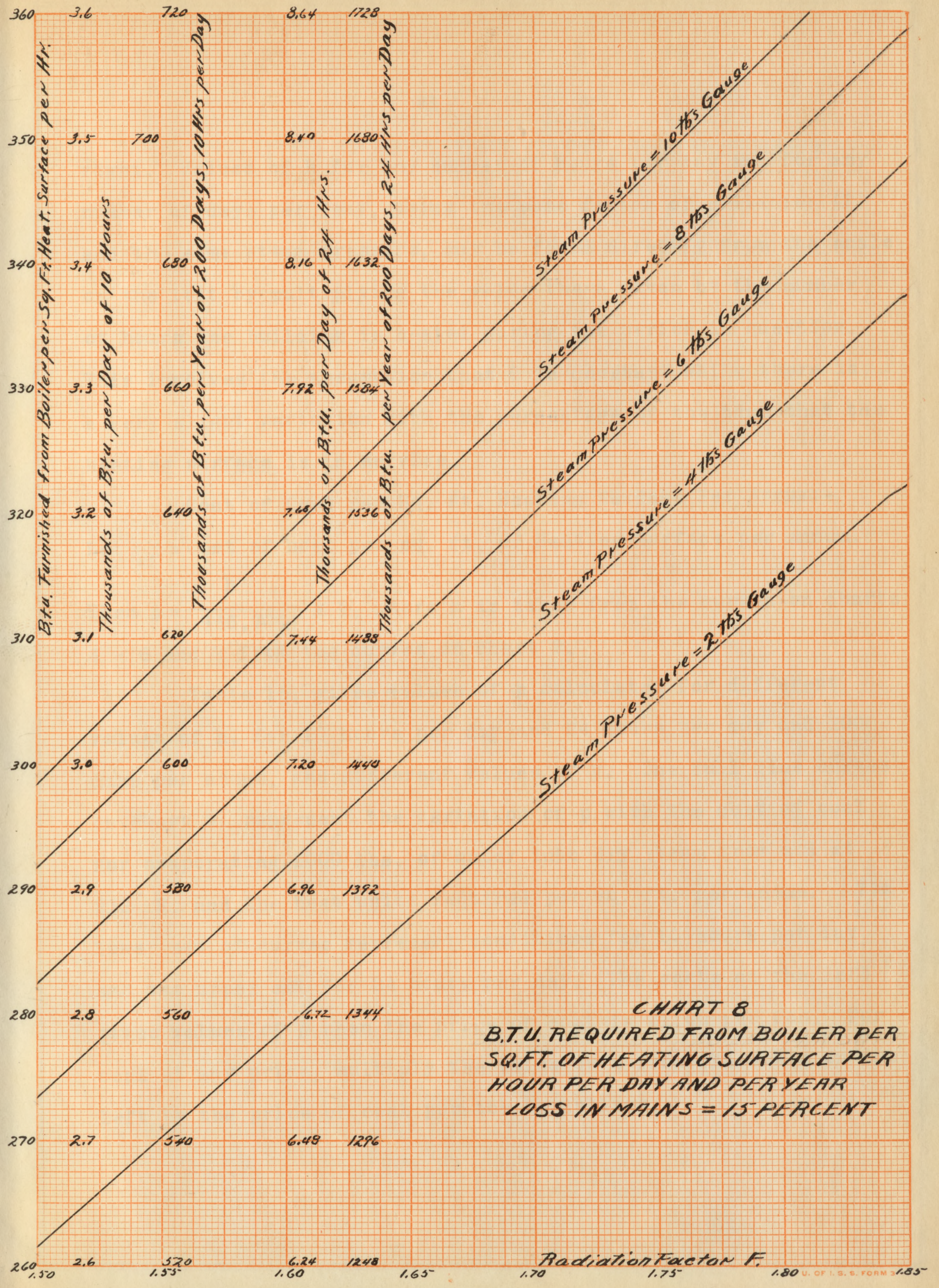


CHART 8
B.T.U. REQUIRED FROM BOILER PER SQ.FT. OF HEATING SURFACE PER HOUR PER DAY AND PER YEAR
LOSS IN MAINS = 15 PERCENT

right. Values of h for any number of hours per day and for any number of days per year, using the same factor of radiation (F) and the same steam pressure, may be found directly from the scale on the left by multiplying the value there given by the number of hours the building is heated during the period in question. This involves the assumption that C is constant while there is a very slight variation with the percentage of the time that the heating surface is in service.

Cost of Coal per Sq. Ft. Heating Surface Per Annum:-

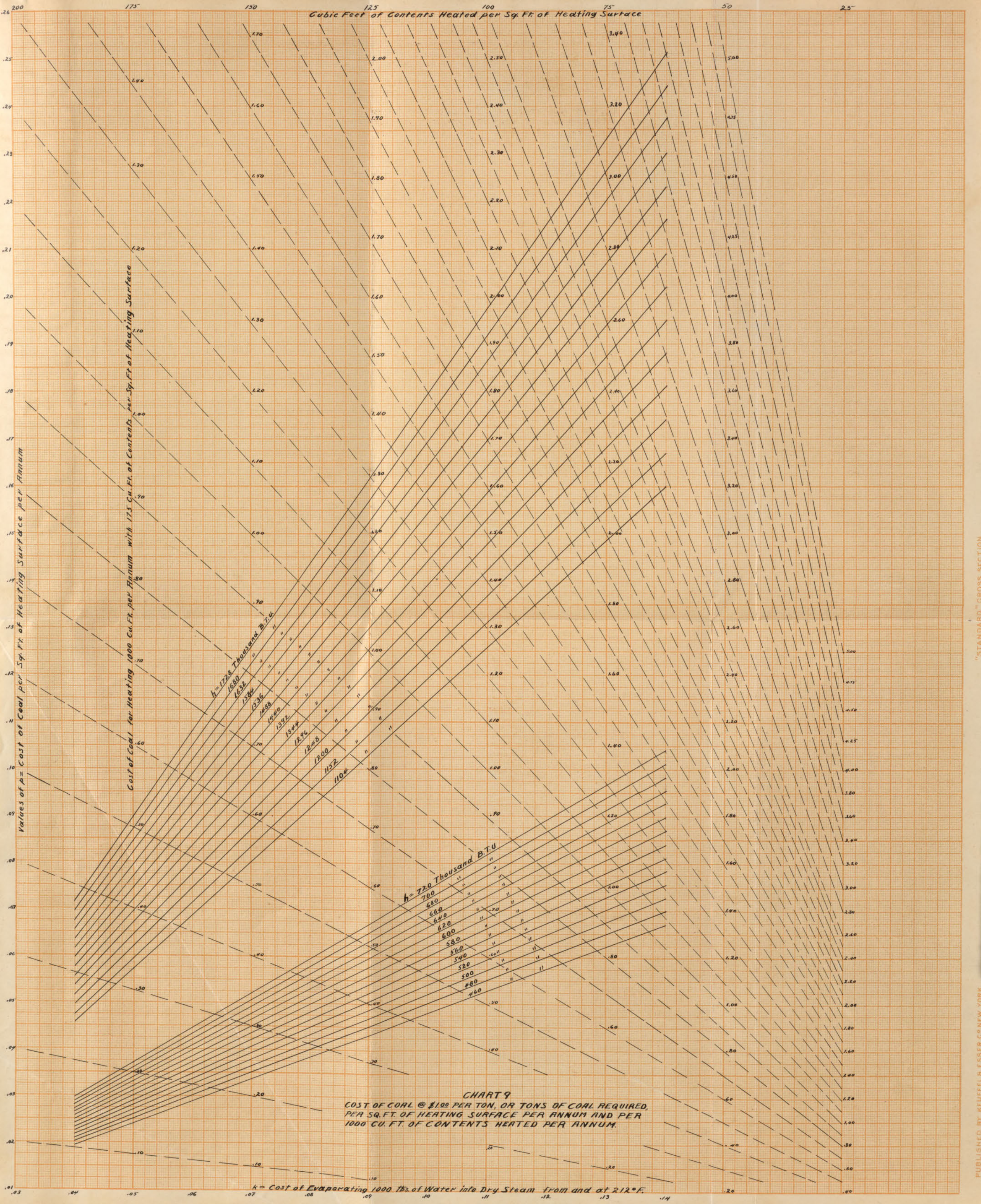
Let p = cost of coal per sq. ft. of Heating Surface per annum.

Then $p = \frac{h}{965,700} \times k$, where h is taken from the curves on charts 4 - 8 and k from the curves on chart 2.

Table 15, gives values of p calculated for different values of h, for 10 hours per day and 24 hours per day and 200 days per annum, and different values of k. The full line curves on chart 9 represent the variation of p with the cost of coal for evaporating 1000 lbs. of water into dry steam from and at 212° F. and the heat units required per sq. ft. per annum. The lower set of curves represent conditions for 10 hours per day and the upper set for 24 hours per day. The scale on the left gives values of p when the price of coal is $1.00 per ton. For coal at any price, multiply the value of p from the scale on the left by the price of coal per ton in dollars.

TABLE 15 - COST OF COAL @ \$1.00 PER TON, OR TONS OF COAL, PER SEASON OF 200 DAYS FOR SUPPLYING STEAM TO ONE SQ. FT. OF HEATING SURFACE.

Values of k---			.04	.05	.06	.07	.08	.09	.10	.11	.12	.13	.14
	h in Thousands	$\frac{h}{965,700}$	$P = k\frac{h}{965,700}$										
10 Hours per Day	460	.476	.0190	.024	.029	.033	.038	.043	.048	.052	.057	.062	.067
	480	.497	.0199	.025	.030	.035	.040	.045	.050	.055	.060	.065	.070
	500	.518	.0207	.026	.031	.036	.041	.047	.052	.057	.062	.067	.073
	520	.538	.0215	.027	.032	.038	.043	.049	.054	.059	.065	.070	.075
	540	.559	.0224	.028	.034	.039	.045	.050	.056	.062	.067	.073	.078
	560	.579	.0232	.029	.035	.041	.046	.052	.058	.064	.070	.075	.081
	580	.601	.0240	.030	.036	.042	.048	.054	.060	.066	.072	.078	.084
	600	.621	.0249	.031	.037	.044	.050	.056	.062	.068	.075	.081	.087
	620	.642	.0257	.032	.038	.045	.051	.058	.064	.071	.077	.084	.090
	640	.663	.0265	.033	.040	.046	.053	.060	.066	.073	.080	.086	.093
	660	.683	.0273	.034	.041	.048	.055	.062	.068	.075	.082	.089	.096
	680	.704	.0282	.035	.042	.049	.056	.063	.070	.078	.085	.092	.099
	700	.725	.0290	.036	.044	.051	.058	.065	.073	.080	.087	.094	.102
	720	.746	.0298	.037	.045	.052	.060	.067	.075	.082	.090	.097	.104
24 Hours per Day	1104	1.14	.046	.057	.069	.080	.092	.103	.114	.126	.137	.149	.160
	1152	1.19	.048	.060	.072	.084	.095	.107	.119	.131	.143	.155	.167
	1200	1.24	.050	.062	.075	.087	.099	.112	.124	.137	.149	.162	.174
	1248	1.29	.052	.065	.078	.091	.103	.116	.129	.142	.155	.168	.181
	1296	1.34	.054	.067	.081	.094	.107	.121	.134	.148	.161	.175	.188
	1344	1.39	.056	.069	.084	.097	.111	.125	.139	.153	.167	.181	.195
	1392	1.44	.058	.072	.087	.101	.115	.130	.144	.159	.173	.187	.202
	1440	1.49	.060	.075	.090	.104	.119	.134	.149	.164	.179	.194	.209
	1488	1.54	.062	.077	.092	.108	.123	.139	.154	.170	.185	.200	.216
	1536	1.59	.064	.080	.095	.111	.127	.143	.159	.175	.191	.207	.223
	1584	1.64	.066	.082	.098	.115	.131	.148	.164	.180	.197	.213	.230
	1632	1.69	.068	.085	.101	.118	.135	.152	.169	.186	.203	.220	.237
	1680	1.74	.070	.087	.104	.122	.139	.157	.174	.191	.209	.226	.244
	1728	1.79	.072	.090	.107	.125	.143	.161	.179	.197	.215	.233	.251



Cubic Feet of Contents Heated per Sq. Ft. of Heating Surface
Values of p = Cost of Coal per Sq. Ft. of Heating Surface per Annum
Cost of Coal for Heating 1000 Cu. Ft. per Annum with 175 Cu. Ft. of Contents per Sq. Ft. of Heating Surface
h = 1728 Thousand B.T.U.
h = 720 Thousand B.T.U.
CHART 9
COST OF COAL @ $1.00 PER TON, OR TONS OF COAL REQUIRED, PER SQ. FT. OF HEATING SURFACE PER ANNUM AND PER 1000 CU. FT. OF CONTENTS HEATED PER ANNUM.
k = Cost of Evaporating 1000 lbs. of Water into Dry Steam from and at 212° F.

COST OF COAL PER 1000 CU. FT. CONTENTS HEATED

Derivation of Formula:-

Let $S =$ cubic contents of any building heated,

$R =$ Sq. Ft. of heating surface in same building,

$g = \frac{S}{R} =$ cu. ft. contents per sq. ft. heating surface.

$r = \frac{1000}{g} =$ Number of sq. ft. of heating surface per 1000 cu. ft. contents.

$P =$ Cost of Coal per 1000 cu. ft. of contents heated per annum.

Then $P = p \times r$ where p is the cost of coal per sq. ft. of heating surface per annum.

Table 16, which is taken from Carpenter's "Heating and Ventilation of Buildings", gives the average of the values of "g" most commonly used for buildings of different character.

On Chart 9 values of "g" are marked off along the top of the chart from right to left. The full line curves represent P, or the cost of coal for heating 1000 cu. ft. of contents per annum, to the different vertical scales marked off on the chart, the price of coal being $1.00 per ton of 2,000 lbs. Each of the vertical scales, except the one on the extreme left, corresponds to the value of "g" at the top of the chart. The "dashed" curves are drawn through points of constant cost of coal and serve the same purpose as marking off scales for every possible value of g between 25 and 200, or for all values of r from 40 to 5.

TABLE 16 - CRUDE ESTIMATE OF THE CUBIC FEET OF SPACE HEATED BY ONE SQ. FT. OF DIRECT LOW-PRESSURE STEAM HEATING SURFACE.

	Authority	A	B	C	D	E	Average	$r = \frac{1000}{9}$
Dwellings	First Floor	35 to 60		35 to 50			45	22.2
	Second Floor	50 to 80		50 to 70			62.5	16
	Average		60 to 80		50		60	16.67
	Living Rooms					50	50	20
	One Side Exposed					50	50	20
	Two Sides Exposed					45	45	22.2
	Three "					40	40	25
	Halls and Bath Rooms					40 to 50	45	22.2
	Sleeping Rooms					60 to 75	67.5	14.8
Public Buildings	Offices	50 to 80 35 to 60	60 to 80		70	50 to 75	65	15.4
	Banks				70		70	14.3
	School Rooms	50 to 80 35 to 60	60 to 80			60 to 80	65	15.4
	Factories	75 to 100				80 to 100	90	11.1
	Stores, Wholesale	75 to 100	100		150	80 to 100	107	9.4
	" Retail		75		125		100	10
	" Dry Goods				80		80	12.5
	" Drugs				70		70	14.3
	Assembly Halls	75 to 100	75 to 100			100 to 150	100	10
	Auditoriums	125 to 200	75 to 100				125	8
	Churches	125 to 200	150 to 200		200	100 to 150	165	6.1
	Large Hotels				125		125	8

These curves can easily be drawn for intermediate values of P, but in order to avoid confusion they have been drawn here only at intervals of $0.10. Since these vertical scales give the cost of coal for heating 1000 cu. ft. contents per annum with coal costing $1.00 per ton, the same values represent the tons of coal required per 1000 cu. ft. of contents heated per annum. For coals at any price multiply the value of P taken from the chart by the price of coal per ton in dollars.

As an illustration of the use of these formulas and curves take a central heating station furnishing steam to the direct low-pressure steam heating surface of a large office building which is heated, say 10 hours per day and 200 days per season, and in which there are, say 70 cu. ft. contents per sq. ft. of heating surface installed. The heating surface consists of ordinary two and three column cast iron radiators from 26 to 38 inches high. The steam enters at an average pressure of 6 lb. per sq. in., gauge. The loss in the steam mains taken for the entire season amounts to 7.5 per cent of the heat supplied to the mains. The coal burned has an average heating value of 11,500 B.t.u. per lb. and costs $3.50 per ton of 2000 lb. delivered. The average boiler efficiency is 60 per cent. What is the cost of coal for supplying steam per sq. ft. of heating surface per annum, and what is the cost of coal per 1000 cu. ft. of contents heated per annum?

From chart 2, for $E = 60$ and $H = 11,500$ we get, $k = \$0.07$

when coal costs \$1.00 per ton. For a system of this character we may take the factor of radiation, $F, = 1.60$ B.t.u. per sq. ft. per hour per degree difference between temperatures of steam and room.

Referring to chart 5, for $C = 7.5$, $F = 1.60$, steam pressure 6 lbs., 10 hrs. per day and 200 days per season, we get,-

$h = 554,000$ B.t.u.

Then from chart 9, we find $k = 0.07$ on the horizontal scale at the bottom, move from here upward along a vertical line until it cuts the curve $h = 554,000$ B.t.u. (not drawn, but lies between $h = 540,000$ and $h = 560,000$) and from here move over to the scale on the extreme left where we find, $p = \$0.04$.

Next we move along the same horizontal line until it cuts the vertical line marked 70 at the top, and we find, $P = \$0.57$.

These are the values for coal at \$1.00 per ton.

Multiplying each by 3.50 we get,-

$0.04 \times 3.50 = \$0.14 =$ cost of coal, per sq. ft. of heating surface per annum.

$0.57 \times 3.50 = \$2.00 =$ cost of coal for heating 1000 cu. ft. contents per annum.

To illustrate further the use of chart 9, let us suppose in the design of this system we assume that the cost of coal shall not exceed \$1.50 per 1000 cu. ft. of contents heated per annum, the cost of coal and the conditions of evaporation and transmission remaining the same as above stated. Then the ratio of the cu. ft. of contents to the sq. ft. of heating surface installed, or the value of g, must be increased. To find the new value of g proceed as follows:-

$\frac{1.50}{3.50} = 0.43$ = cost of coal at 1.00 per ton or the tons of coal allowed per 1000 cu. ft. contents per annum = P.

Move along the horizontal line marked .04 on the left to its intersection with the dashed line .43 (not drawn) and then vertically to the scale at the top. This gives g = about 95.

RECAPITULATION

For the sake of clearness the formulas and notation given above are here repeated.

H = Heating value of one lb. of coal as fired, B.t.u.

K = Cost of one ton of coal of 2000 lbs., $—

E = Efficiency of Boiler and Grate, per cent

M = Thousands of lbs. of water evaporated into dry steam from and at 212° F. per ton of coal as fired.

k = Cost of evaporating 1000 lbs. of water into dry steam from and at 212° F., $—

F = B.t.u. emitted per sq. ft. of heating surface per hour per degree difference between temperatures of steam and room.

dT = Degrees difference between temperature of steam and room.

Q = F$\times$dT = B.t.u. emitted per sq. ft. heating surface per hour.

n_1 = Number of hours building is heated per day.

n_2 = Number of days building is heated per year.

C = Percentage of total heat supplied from boiler lost in mains.

h = B.t.u. required at boiler to furnish steam to one sq. ft. of heating surface for any period.

p = cost of coal per sq. ft. of heating surface per annum.

S = cubic contents of building.

R = sq. ft. of heating surface in operation.

$g = \frac{S}{R}$ = cu. ft. contents per sq. ft. heating surface.

$r = \frac{1000}{g}$ = Number of sq. ft. of heating surface per 1000 cu. ft. of contents.

P = Cost of coal per 1000 cu. ft. contents heated per annum.

$$M = \frac{H\ E}{100} \times \frac{2000}{965700} = \frac{E\ H}{48285}$$

$$k = \frac{K}{M} = \frac{48285\ K}{H\ E}$$

$$h = \frac{Q \times n_1 \times n_2}{\left(1 - \frac{C}{100}\right)}$$

$$p = \frac{h}{965700} \times k$$

$$P = p \times r$$

The following diagram will aid the reader in keeping in mind the variables on which the value of P is dependent:-

P depends on
- p, depends on
  - h, depends on
    - Q, depends on
      - F, depends on the construction of the radiators and the circulation of the air. dT, depends on steam pressure.
    - n_1, depends on use of building
    - n_2, depends on use of building.
    - C, depends on length, size and condition of mains.
  - k, depends on
    - K
    - M, depends on
      - E
      - H
- r, depends on g, depends on use, construction and exposure of building.

Tests for the value of the factor F comprise almost all of Chapter I of this work. The average value there found is about 1.60. The value of dT ranges usually between 145 and 170, depending on the steam pressure, an average value being about 160. n_1 ranges usually from 4 or 5 to 24 depending on the use made of the building and the opinion of the operator as to whether it is more economical to heat from smaller surface for a longer period of time, or from greater surface for shorter periods. n_2 likewise depends on the use of the building and ranges from 1 or 2 days per week for churches, Auditoriums, Opera Houses, etc. to 7 days per week in offices, living rooms, etc. Tests for the value of C in the central station heating system at the University of Illinois are recorded in Chapter II of this work. There is given also a method of finding C for similar cases. K depends on the location of the plant with reference to coal mines and the grade of coal the plant is capable of burning. The grade of coal burned and, consequently, the value of H depends on the location of the plant with reference to the coal mines, and the facility for burning low grade coals. In general the poorer grades of coal can be burned to advantage near the mines, but it is not profitable to pay excessive freight on them. The wide range in the value of g is clearly shown in table 16.

COST OF SUPPLYING HEAT AT THE UNIVERSITY OF ILLINOIS

The following investigation was made for the winter of 1908 - 1909 and, consequently, statements here made apply to the system as it then existed.

Description of System:- in fig. 2, Chapter II, is given a plan of the greater part of this heating system. There is a shorter tunnel, 815 ft. in length, running North from the heating station and there is a low-pressure main 164 ft. in length running through the boiler and engine rooms. The total length of mains is 5245 ft., 4025 of which is laid in tunnels. Practically all of the mains laid in tunnels are 10" and 9" mains. Those laid under ground range from 2 1/2" to 4" in diameter. The total surface of the low-pressure mains is 12,515 sq.ft. From this system of mains steam is supplied to 129,820 sq. ft. of direct and equivalent direct heating surface, exclusive of the surface of the mains which is equivalent to about 4,500 sq. ft. of direct heating surface. This heating surface is distributed through 25 buildings. The distribution of the heating surface in these buildings is given in table 17. Practically all of the buildings are built of brick except the Library which is of stone. The total number of hours during which each of these buildings was heated during each month and during the entire heating season of 1908 - 1909 is given in table 18. Table 19 gives the average number of hours per day that each building was heated during each month, the average of the same for the entire season and the average for the entire surface for the entire season, the value of the last average being 13.33 hours per day. In the plant which furnishes steam to this system are installed eight boilers whose aggregate capacity is 1770 horse power.

Other Loads:- Besides the heating load, the plant carries a power load, the most of which is used in the adjoining engine room. The exhaust from the engines enters directly into the low-pressure steam mains and is used for heating. Table 20 gives the total and average of this load during the heating season of 1908 1909, and the average metered horse power of the boiler plant. This plant also carries a number of small fluctuating loads among which are, steam for the Steam and Hydraulic Laboratories, steam for the steam baths etc. in the Chemical and Agricultural Build-

TABLE 17 - TOTAL HEATING SURFACE SUPPLIED WITH STEAM FROM THE CENT. HEAT. STATION, 1908-1909

Building	Sq. Ft. of Surface in Radiators				Sq. Ft. of Risers and Other Pipes		Total Radiating Surface			
	Wrough Iron		Cast Iron							
	Direct	Indirect	Direct	Indirect	Exposed	Covered	Direct	Indirect	Direct plus Indirect	Equivalent Direct
Auditorium			3601		1218		4819		4819	4819
Observatory			232		83		315		315	315
Entomology Lab.	357		256				613		613	613
South Green House	2440		320				2760		2760	2760
Agricultural Bldg.			9408		2245		11653		11653	11653
Chemistry Bldg.		1751	5560		1465		7025	1751	8776	15780
Woman's Building	950	648	3040	270	860	784	4850	1702	6552	5735
Y.M.C.A. Building							4000		4000	4000
Library		2893				152		3045	3045	15370
Main Hall	6928	3206	1782		1969		10679	3206	13885	13085
Nat. History Bldg.				6817	1321		1321	6817	8138	6433
Law School							4371	1740	6111	5676
Engineering Bldg.	3594		5783		1590		10967		10967	10967
President's House			1044	340			1044	340	1384	1299
Hydraulics Lab.			1677		568		2245		2245	2245
E.E. Lab. & Power Plant	1142		408		443		1993		1993	1993
Ceramics Bldg.	120						120		120	120
M.E. Laboratory		1000	744		536	478	1280	1478	2758	5400
Road Laboratory	1025		318				1343		1343	1343
North Green House	1156		60				1216		1216	1216
Forge	354						354		354	354
Foundry	1770				1520		3290		3290	3290
Machine Shops	2491		230		753		3474		3474	3474
Store Room	127						127		127	127
Wood Shop			1282		1520		2802		2802	2802
Armory			2261		1245		3506		3506	3506
Gymnasium			4423		1120		5443		5443	5443
Low-Press. Mains						12515		12515	12515	5006
High Press Mains						1616		1616	1616	1616
Totals	22454	9498	42429	7427	18456	15545	91610	34210	125820	135632

TABLE 18 – TOTAL NUMBER OF HOURS EACH BUILDING WAS HEATED DURING EACH MONTH OF AND THE ENTIRE HEATING SEASON OF 1908-1909

Building	Period							
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Sept. 27 to Apr. 24
Gymnasium	274.5	317	396	499	326.5	441.5	215.5	2470
Armory	0	147	317.5	575	492	732	552	2828
Wood Shop	42	211	298	402	219	301	147.5	1620
Machine Shop	104.5	216.5	393	402	218	292.5	150.5	1677
Mech. Eng. Lab.	45	274.5	340	428.5	240	422.5	179.5	1930
Elec. Eng. Lab.	72.5	228.5	297	410	222.5	294.5	155	1680
Ceramics Bldg.	336	720	744	744	504	744	576	4368
Hydraulics Lab.	263.5	271.5	306.5	444.5	158.5	308	182	2035
Engineering Hall	188.5	265	335	438.5	247.5	354.5	203	2032
President's House	769	676.5	744	744	504	744	576	4758
North Green House	648	720	576	744	504	744	576	4512
Library	534	648	720	744	504	744	552	4446
Main Hall	301.5	324.5	399	456.5	265.5	341	173.5	2262
Law School	230	410.5	447	505.5	326.5	449	217.5	2585
Nat. History Bldg.	203	276.5	329	422.5	244	309.5	169.5	1954
Chemistry Bldg.	209	310	398	501.5	279	387	287	2372
Agricultural Bldg.	231	299	401	505	306	418	214.5	2375
South Green House	648	720	744	744	504	744	576	4680
Entomology Bldg	480	720	744	744	504	744	576	4512
Auditorium	53	243.5	346.5	428.5	255.5	313	111.5	1752
Woman's Building	155	270	348	413	303	324.5	167	198
Steam Mains	840	720	744	744	504	744	576	4872
Steam Mains, Entire Year	8592							

TABLE 19—AVERAGE NUMBER OF HOURS EACH BUILDING WAS HEATED PER DAY DURING EACH MONTH OF AND THE ENTIRE HEATING SEASON OF 1908–1909

Building	Period							
	Oct.	Nov.	Dec.	Jan.	Feb	Mar	Apr.	Sept. 27 to Apr. 24
Gymnasium	7.8	10.6	12.8	16.1	15.6	14.2	9.0	12.2
Armory	0	4.9	10.2	18.6	23.4	23.6	23.0	13.9
Wood Shop	1.2	7.0	9.6	13.0	10.4	9.7	6.2	8.0
Machine Shop	3.0	7.2	12.7	13.0	10.4	9.4	6.3	8.3
Mech. Eng. Lab.	1.3	9.2	11.0	13.8	11.4	13.6	7.5	9.5
Elec. Eng. Lab.	2.1	7.6	9.6	13.2	10.6	9.5	6.5	8.3
Ceramics Bldg.	9.6	24	24	24	24	24	24	21.5
Hydraulics Lab.	7.5	9.1	10.0	14.4	7.6	9.9	7.6	10.0
Engineeing Hall	5.4	8.8	10.8	14.2	11.8	11.4	8.5	10.0
President's House	22.0	22.6	24	24	24	24	24	23.4
North Green House	18.5	24	18.6	24	24	24	24	22.2
Library	15.3	21.6	23.2	24	24	24	23	21.9
Main Hall	8.6	10.8	12.9	14.7	12.6	11.0	7.2	11.1
Law School	6.6	13.7	14.4	16.3	15.6	14.5	9.1	12.7
Nat. History Bldg.	5.8	9.2	10.6	13.6	11.6	10.0	7.1	9.6
Chemistry Bldg.	6.0	10.3	12.8	16.2	13.3	12.2	12.0	11.7
Agricultural Bldg.	6.6	10.0	12.9	16.3	14.6	13.5	8.9	11.7
South Green House	18.5	24	24	24	24	24	24	23.1
Entomology Bldg.	13.7	24	24	24	24	24	24	22.2
Auditorium	1.5	8.1	11.2	13.8	12.2	10.1	4.7	8.6
Woman's Bldg.	4.4	9.0	11.2	13.3	14.4	10.5	7.0	9.8
Average for all the Buildings, each Valued according to the Magnitude of its System								13.33

TABLE 20 - TOTAL AND AVERAGE ELECTRIC LOAD ON THE BOILERS AND THE METERED HORSE POWER DEVELOPED BY THE BOILERS DURING EACH MONTH OF AND THE ENTIRE HEATING SEASON OF 1908-1909

Month		Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Sept. 27 to Apr. 24
Number of Days		35	30	31	31	28	31	24	210
Total K.W. Hours Output	Day	42533	37521	43533	46079	38881	40459	37256	286261
	Night	21424	20337	22148	24594	24037	30158	23926	166623
	Sum	63957	57858	65681	70673	62918	70617	61182	452884
Average K.W. Hours Output	Day	1215	1252	1404	1486	1389	1305	1552	1363
	Night	612	678	714	793	858	973	997	793
	Day & Night	1827	1930	2118	2279	2247	2278	2549	2156
Average Metered H.P.	Day	579	811	980	1002	1044	977	873	888
	Night	323	416	358	656	653	566	475	514
	Day & Night	451	613.5	759	829	848.5	771.5	674	701

ings, steam for the fire and water supply pumps and steam for heating water in the Gymnasiums and wash rooms. A fair extimate of the average value of these loads including the heat taken from the steam in the engines would be about 15 per cent of the average output of the boiler plant.

COST OF COAL PER SQ. FT. OF HEATING SURFACE PER ANNUM

Using the method given above, we have:-

$$\left.\begin{array}{l} F = 1.60 \\ dT = 160 \end{array}\right) Q = 256$$

From table 19,

$$n_1 = 13.33$$

$$n_2 = 210$$

From table 9, Chapter II,

$$C = 8.58$$

$$1 - \frac{C}{100} = .9142$$

Then $$h = \frac{256 \times 13.33 \times 210}{.9142} = 783,880$$

For the coal used,

$$H = 10,000 \text{ B.t.u.}$$

In table 10, Chapter II, the average efficiency of boiler and grate for ten tests is 57.4 per cent. This is the efficiency of the boiler and grate alone during periods when the boilers tested were developing about rated capacity. If we take into account the steam used by auxiliaries and the losses due to sudden changes of load together with the losses due to banking fires over night etc., the average efficiency of the plant as a steam furnishing plant for the heating season would be reduced to about 50 per cent.

From Chart 2, for $H = 10,000$ and $E = 50.0$ we get $K = \$0.0965$.

Then $p = \frac{h}{965,700} \times k = \frac{783,880}{965,700} \times .0965 = \$0.0784$

Multiplying this by the cost of coal per ton in dollars we have,-

$.0784 \times 1.23 = \$0.096$.

This is the calculated cost of coal per sq. ft. of heating surface from September 27, 1908 to April 24, 1909. The total cost of coal burned in this plant during this period was $14790.36 at $1.23 per ton of 2000 lbs. The total useful heating surface supplied was 129,820. Since about 15 per cent of the load on the boilers was used for purposes other than heating, the cost of coal which should be charged to the heating surface is,-

$14,790.36 \times .85 = \$12571.81$, which gives for the actual cost of coal per sq. ft. of heating surface from September 27, 1908 to April 24, 1909,

$$\frac{12571.81}{129,820} = \$0.097$$

TOTAL COST PER SQ. FT. OF HEATING SURFACE PER ANNUM

The following are the items of the total cost for the heating year 1908 - 1909.

Boiler Plant,-	
Cost of Coal	$14,799.36
Operation	3,374.70
Maintenance, labor and materials	1,032.94
Interest and Depreciation at 12 %	8,400.00
Total	$27,607.00

Only 85 per cent of this should be charged to the heating system.

Heating Mains,-	
Interest and depreciation on mains at 10 %	$ 1,382.90
Interest on cost of tunnels at 5 %	1,006.25
Total	$ 2,389.15
Heating Systems,-	
Operation	525.00
Maintenance, labor and materials	702.24
Interest and depreciation at 10 %	9,256.20
Total	$10,483.44
Totals,-	
Boiler Plant, 27,607.00 × .85	23,465.95
Heating Mains	2,389.15
Heating Systems	10,483.44
Total	$36,338.54

Total Heating Surface supplied = 129,820 sq. ft.

Hense the total cost per sq. ft. per annum is $\frac{36,338.54}{129,820} = \$0.280$

Note! This being State property there is no tax. There are no insurance charges. The depreciation of the tunnels is charged to the electric lines. The cost of water has not been considered.

COST OF COAL PER 1000 CU. FT. OF CONTENTS HEATED PER ANNUM

In table 6, Chapter I, the ratio of the cubic contents heated per sq. ft. of radiator surface for the Engineering Hall, the Physics Building and the Woman's Building is given as 75.5. If instead of the radiator surface we use the total heating surface including the equivalent of the pipe surface this ratio becomes 64. This may be taken as the average for all of the buildings on the Campus, i.e.

$$g = 64$$

$$r = \frac{1000}{64} = 15.6$$

hence the cost of coal per 1000 cu. ft. of contents heated per annum is,-

$$0.097 \times 15.6 = \$1.51$$

TOTAL COST PER 1000 CU. FT. OF CONTENTS HEATED PER ANNUM

The total cost per 1000 cu. ft. of contents per annum is, $0.28 \times 15.6 = \$4.37$.

Arrangement of Figures, Tables and Charts